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Modelling and Analysis Capabilities for Lightweight Masts

T.S. Koko, D.P. Brennan, X. Luo, M.E. Norwood, L. Jiang and U.O. Akpan
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Contract Number: W7707-010696/101/HAL

Contract Scientific Authority: M.J. Smith, 902-426-3100 x383

Defence R&D Canada

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DREA CR 2001-017

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The scientific or technical validity of this Contract Report is entirely the responsibility of the contractor and the contents do not necessarily have the approval or endorsement of Defence R&D Canada

Abstract

This study was undertaken to address modelling and analysis capabilities for metallic and composite mast structures, required by DREA in their effort to investigate lightweight masts for the Halifax Class frigate, as part of midlife refit. The study focussed on three main areas. First, a review of finite element formulations for composite shell structures was performed to provide an understanding of the kinematic theories, failure and damage mechanisms, and element types that can be suitably used for composite mast structures. Next, an overview of metallic and composite mast structures used world-wide was undertaken to identify various mast configurations and finally, the design and development of a prototype mast analysis software (MASTAS) was implemented.

It was shown that finite elements based on the equivalent single-layer (ESL) theories, such as the classical laminate plate (CLPT) and first order shear deformation theory (FSDT) can provide reasonable approximations of global response quantities, such as natural frequencies, buckling loads, strain energy and global displacements. On the other hand, higher order ESL theories or layerwise theories would be required to compute detailed stresses at cutouts, connections and other critical locations. It was also shown that for better accuracy of modelling damage in composites, it is necessary to use progressive failure concepts.

There are four main types of masts, namely, polemasts (stayed and unstayed), tripod, lattice, and enclosed masts used on naval ships. The polemast, the simplest form of mast, is found on naval ships, including some auxiliary Canadian vessels. The lattice mast is by far the most common type found on Canadian as well as other navy ships. The tripod mast, which has the advantage of requiring smaller space for installation (compared to the lattice mast) is found mainly on ships of the US Navy but not Canadian ships. The use of enclosed mast structures (metal or composite) is an emerging technology that is being considered by several industrialized countries such as the USA, UK and Netherlands, and some demonstration structures have been reported. Metals (steel and aluminum) are traditionally used for mast construction, but their use poses problems such as weight, maintenance (corrosion induced) and electromagnetic interference. Composite materials are now being considered because of their lightweight, high strength and stiffness, good corrosion resistant properties and superior stealth properties. These activities are expected to increase in the present decade and beyond.

Based on the results of the review, the requirements of the mast modelling software system were identified and developed. The software design specified an object-oriented software for operation in a Windows based operation system on a personal computer (PC). The DREA developed hierarchical object oriented data management (HOOD) toolkit was selected as the software development platform. A prototype software (called MASTAS) was developed. It was shown that the program could be used to rapidly generate, plot and manipulate geometric models of lattice and enclosed mast structures, thus illustrating the feasibility and merit of the software system. Activities required to produce a completely functional software system have been recommended.

Résumé

La présente étude a été entreprise pour évaluer les capacités de modélisation et d'analyse des structures de mâts métalliques et composites requises par le CRDA, qui étudie les mâts légers pour les frégates de la classe Halifax, dans le cadre d'une modernisation à mi-vie. L'étude a porté sur trois points principaux. Premièrement, un examen des méthodes d'expression par éléments finis pour les structures en composite a été effectué pour bien comprendre les théories cinématiques, les mécanismes de défaillance et de dommages, ainsi que les types d'éléments pouvant servir aux structures des mâts composites. On a prodédé ensuite à un examen des structures des mâts métalliques et composites utilisés dans le monde pour identifier diverses configurations de mâts; enfin, la conception et le développement d'un prototype de logiciel d'analyse de mât (MASTAS) ont été entrepris.

Il s'est avéré que les éléments finis se basant sur les théories équivalentes sur les monocouches, comme le lamellé classique et la théorie des cisaillements de premier ordre peuvent donner des approximations raisonnables des valeurs de réponse globale comme les fréquences propres, les charges de flambage, l'énergie de déformation et les déplacements totaux. Par contre, les théories monocouches équivalentes supérieures, ou théories des couches, seraient nécessaires pour calculer en détail les contraintes aux ouvertures, aux connexions et aux autres emplacement critiques. Il est également apparu que pour obtenir une meilleure précision de la modélisation des dommages sur les matériaux composites, il est nécessaire d'avoir recours à des notions de défaillance progressive.

Quatre types principaux de mâts sont utilisés sur les navires : le mât à pible (haubané ou non), le mât tripode, le mât en treillis et le mât à structure fermée. Le mât à pible, le type le plus simple, équipe les navires de guerre, y compris certains navires auxiliaires canadiens. Le mât en treillis est de loin le type que l'on retrouve le plus souvent sur les navires canadiens, de même que sur les navires d'autres marines. Le mât tripode, qui a l'avantage d'exiger moins d'espace pour son installation (par rapport au mât en treillis) équipe surtout les navires de la US Navy, mais pas les navires canadiens. Le mât à structure fermée (métallique ou composite) est une technologie nouvelle qui est envisagée par plusieurs pays industrialisés comme les États-Unis, le Royaume Uni et la Hollande, et certaines structures ont été utilisées à des fins de démonstration. Les métaux (l'acier et l'aluminium) sont généralement utilisés pour la construction des mâts, mais ils posent des problèmes, comme par exemple le poids, l'entretien (à cause de la corrosion) et les interférences électromagnétiques. Les matériaux composites sont maintenant envisagés en raison de leur légèreté, leur résistance et leur rigidité élevées, une bonne résistance à la corrosion et leur excellente furtivité. On s'attend à ce que leur utilisation s'accroisse au cours de la décennie présente et dans le futur.

Executive summary

Introduction

A lightweight mast is being considered for the HALIFAX class frigate as part of its mid-life re-fit. In response to this, a DRDB Technical Application project was proposed and accepted. It is expected that the work undertaken in this project will provide DREA with the tools to perform structural assessments of conventional and composite warship masts, and to investigate design alternatives in a timely fashion. This report describes the first phase of the contract work that was completed under this project, the overall aim being to upgrade modelling and analysis capabilities for mast structures and composite materials.

Principal Results

A prototype of a rapid finite element modelling software tool for warship masts (MASTSAS) has been designed and developed. The MASTSAS prototype, which was developed using DREA's HOOD programmer's toolkit, provides basic geometric modelling capabilities for lattice and enclosed masts, including the creation of multi-bay trunks, yardarms and auxilliary trunk components, as well as attachments between these components. In addition to this work, literature surveys were compiled in the areas of warship masts and composite finite element technology.

Significance of Results

The work completed in this project provides the groundwork for the further development of the MASTSAS modelling tool in FY00/01 and FY01/02. The literature surveys performed in this study will aid in this task. The findings of the composite finite element survey will assist in determining what additional capabilities will be needed in DREA's VAST finite element code in order to be able to analyse composite mast structures.

Future Plans

The second phase of this Technology Application project is currently underway, and is primarily concerned with completing the development of MASTSAS's geometric modelling capabilities, and the creation of materials and properties databases. A further phase is scheduled for FY01/02, which will see the development of finite element meshing capabilities, and the development of finite element load cases specialised to mast applications.

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Sommaire

Introduction

On envisage un mât léger pour les frégates de la classe HALIFAX dans le cadre d'une modernisation à mi-vie. Dans cette perspective, le projet d'application technique du DRDD a été proposé et accepté. On s'attend à ce que les travaux entrepris dans le cadre de ce projet donnent au DRDA les outils permettant d'effectuer les évaluations structurales des mâts classiques ou composites pour navires de guerre, et de rechercher des conceptions de remplacement en temps voulu. Le présent rapport décrit la première phase des travaux qui ont été effectués sous contrat dans le cadre de ce projet, le but principal étant d'améliorer les capacités de modélisation et d'analyse des structures de mâts et des matériaux composites.

Principaux résultats

Un prototype de logiciel de modélisation rapide par éléments finis pour des mâts de navires de guerre (MASTSAS) a été conçu et développé. Ce prototype, qui a été développé à l'aide de l'outil de programmation HOOD du DRDA, donne des capacités de modélisation géométriques de base pour les mâts en treillis et les mâts à structure fermée, y compris la création de composant pour troncs à sections multiples, flèches et troncs auxiliaires, de même que les raccords entre ces composants. En plus de ce travail, des examens de documentation ont été compilés dans les domaines des mâts de navires de guerre et de la technologie des éléments finis composites.

Importance des résultats

Les travaux effectués pour ce projet fournissent la base du développement futur de l'outil de modélisation MASTAS des exercices financiers 2000/2001 et 2001/2002. Les examens de documentation exécutés au cours de cette étude aideront à cette tâche. Les résultats de l'examen des éléments finis composites contribueront à déterminer quelles capacités supplémentaires seront nécessaires à la formule des éléments finis VAST du DRDA pour pouvoir analyser les structures des mâts composites.

Projets futurs

La deuxième phase de ce projet d'application de technologie est actuellement en cours et s'attache surtout à terminer le développement des capacités de modélisation géométrique de MASTSAS, ainsi qu'à créer des bases de données sur les matériaux et leurs propriétés. Une autre phase est prévue pour l'exercice financier de 2001/2002 et concerne le développement des capacités d'engrènement des éléments finis et des contraintes des éléments finis pour les mâts.

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1. INTRODUCTION

1.1 Background

Canadian warships are generally equipped with unstayed lattice mast structures that are used to support navigational and weather instruments and various electronic devices such as radar antennas. These structures are traditionally constructed of metallic materials such as steel and aluminum. The use of these materials poses some problems in terms of the design, maintenance and operation. For instance, the optimal design of lattice masts aimed at reducing weight and profile area and increasing their ability to absorb energy is still a topic of current research (Ellis et al., 1998; Liang et al., 1994). In addition, metals are susceptible to corrosion in the marine environment, which can lead to high maintenance costs. Furthermore, the use of metals lead can also lead to interference with radar and other electromagnetic equipment. Advanced composite materials offer many advantages, including weight savings, incorporation of radar absorbing materials and corrosion resistance and are gaining wider acceptance for use on board naval warships. These materials can be used either by themselves or in combination with metals to reduce or eliminate some of the disadvantages associated with the use of metals alone.

1.2 Objectives and Scope

This report addresses the requirement for a lightweight mast for the Halifax Class frigate as part of mid-life refit. An initial step in fulfilment of this requirement is to upgrade the modelling and analysis capabilities for mast structures, including composite structures. Of particular interest are advanced finite element modelling and analysis capabilities for enclosed and lattice lightweight masts. The specific objectives of the study include:

(i) To conduct a review of finite element formulations for composite shells;
(ii) To conduct a review of metallic and composite masts structures; and
(iii) To design and develop a prototype software system for rapid modelling of masts.

The review of finite element formulations for composite shells is provided in Chapter 2, where various kinematic theories, linear and nonlinear constitutive relations, element formulations and applications are discussed. In Chapter 3, a review of composite masts, covering mast configuration, their design, fabrication and performance evaluation is provided. Chapter 4 discusses the requirements and design of the software system for rapid modelling of masts. The development, implementation and demonstration of a prototype software system are discussed in Chapter 5. Summary and conclusions of the study, including recommendations for future work, are provided in Chapter 6.

2 REVIEW OF FINITE ELEMENT FORMULATIONS FOR COMPOSITES

2.1. Introduction

This chapter is concerned with the review of finite element formulations for composite materials/structures. The finite element method is now widely used to solve a wide range of engineering problems, because of its versatility and ability to model complex structural configurations, constitutive behaviour, loading and boundary conditions. Detailed descriptions of the finite element methodology can be found in standard texts, such as Bathe, 1982 and Cook et al., 1989. In general, the formulation of a finite element methodology for solving structural engineering problems involves the following steps:

- Development of kinematic relations (including element design, shape functions and strain-displacement relations);
- Development of constitutive relations;
- Development of the equations of motion;
- Development of techniques for the solution of the equations of motion; and
- Computer implementation and testing of the formulations.

The review covers the issues involved in these main steps. However, emphasis is placed on the first two steps, namely the development of kinematic and constitutive relations. The last three steps, namely the development of equation of motion, solution techniques and computer implementation, are only given a brief mention, due to the fact that the issues involved are similar to the case of isotropic materials, which have been discussed extensively in standard texts such as Bathe, 1982 and Cook et al., 1989. The kinematic theories for composite laminates are discussed in Section 2.2, whereas Section 2.3 provides details of the constitutive relations for composites. Some specific finite elements developed for modelling composites are presented in Section 2.4. Representative applications of finite element formulations for composite structures are discussed in Section 5.

2.2 Kinematic Theories for Composite Laminates

The subject of plate and shell theories for composite structures continues to attract attention in the science and engineering research community, and many theories can be found in the

literature. In general, these theories can be classified into three main categories (Bose and Reddy, 1998), namely,

- Equivalent single layer (ESL) 2-D theories;
- Layerwise (LW) 2-D theories; and
- Continuum based 3-D theories.

In addition to these, there are sandwich plate theories for modeling the behaviour of sandwich composite structures. These theories are reviewed in the following subsections.

2.2.1 Equivalent Single Layer (ESL) 2-D Theories

The equivalent single layer (ESL) theories are the most commonly used theories for modelling the behaviour of composite structures. In these theories, the heterogeneous laminated composite is treated as a statically equivalent single layer, reducing the 3-D continuum problem to a 2-D problem. The displacements or stresses are expanded as a linear combination of the thickness co-ordinate and undetermined functions of position in the reference surface:

$$\phi_i(x, y, z) = \sum_{j=0}^{N_i} \phi_i^j(x, y)(z)^j, \quad (i = 1,2,3) \tag{2.1}$$

where ϕ_i is the ith component of displacement or stress, ϕ_i^j are functions to be determined, N_i are the numbers of terms in the expansion, and x, y, z represent the three co-ordinate directions, z being the thickness co-ordinate.

Classical Laminate Plate Theory

The simplest of the ESL theories is the classical Laminate Plate Theory (CLPT) (Timoshenko and Woinsky-Kreiger, 1987), which is an extension of the classical (Kirchhoff) plate theory to laminate composite plates (Lekhnitskii, 1981). The classical plate theory is based on the assumptions that straight lines perpendicular to the midplane before deformation remain:

i. Straight;
ii. Inextensible; and

iii. Normal to the midsurface,

after deformation. These assumptions lead to the neglect of transverse strains, ε_{xz}, ε_{yz} and ε_{zz}, which lead to the neglect of transverse stresses σ_{xy}, σ_{yz} and σ_{zz} for composites constructed of orthotropic laminates (Ochoa and Reddy, 1992, Reddy, 1997, 1998). In extending the Kirchhoff plate theory to laminated composites, it is further assumed that the layers are perfectly bonded together. By the CLPT the displacement field u,v,w of a point $P(x, y, z)$ at any given time is given by

$$\begin{aligned} u(x, y, z) &= u_o(x, y) - z\frac{\partial w_o}{\partial x} \\ v(x, y, z) &= v_o(x, y) - z\frac{\partial w_o}{\partial y} \\ w(x, y, z) &= w_o(x, y) \end{aligned} \tag{2.2}$$

where $u_{o,}, v_{o,}, w_o$ are the displacement components along the x,y,z co-ordinate directions, respectively of a point in the midplane (Reddy, 1996, Ochoa and Reddy, 1992).

The classical plate theory is adequate for the analysis of thin plates, in which transverse deformation is negligible. It should also be noted that composites with large direct to shear modulus ratios $(E_{11}/G_{13}, E_{11}/G_{23})$ that is, materials with very low transverse module (G_{13} and G_{23}), are susceptible to thickness failures because strength allowables for transverse stress are correspondingly much lower than in-plane stress allowables. Since the transverse stresses are not considered in the CPLT then the theory should not be used if the composite is likely to fail in transverse shear (Ochoa and Reddy, 1992).

In all the ESL theories, the displacements and strains are continuous through the laminate thickness (that is single valued at the interfaces) of the layers. However, the stress may be discontinuous because of different elastic coefficients at the layer interfaces.

First Order Shear Deformation Theories

Several studies have been carried out to include the effect of transverse shear

deformations in composite theories. The simplest theory to take into account transverse shear deformation is the First Order Shear Deformation Theory (FSDT). As with the CLPT, this theory accounts for linear variation of in-plane displacements through the thickness (Bose and Reddy, 1998; Whitney and Pagano, 1970; Mindlin, 1951; Reissner, 1945):

$$\begin{aligned} u(x,y,z) &= u_0(x,y) + z\phi_x(x,y) \\ u(x,y,z) &= v_0(x,y) + z\phi_y(x,y) \\ u(x,y,z) &= w_0(x,y) \end{aligned} \tag{2.3}$$

where ϕ_x and ϕ_y are the rotations of the transverse normal about the x- and y-axes, respectively, and u_o, v_o, w_o are the midsurface displacement components in the x,y,z directions, respectively. The difference between the FSDT and CLPT is that in the FSDT theories, normals to the midplane remain straight but not necessarily normal to the deformed surface. Hence, the rotations ϕ_x and ϕ_y are not equal to $-\frac{\partial w_0}{\partial x}$ and $-\frac{\partial w_0}{\partial y}$, respectively, as is the case for the CLPT. The FSDT provides a state of constant shear strain through the thickness which deviates from the quadratic variation stipulated by 3-D elasticity theory. This discrepancy is accounted for by the use of the so-called shear correction factor.

Higher Order Theories

Numerous higher order shear deformation theories have been developed in order to provide better approximation of the shear strain through the thickness. These higher order (N>1 in equation 2.1) theories are obtained by removing the inextensibility and/or straightness of the transverse normals conditions. In these theories, the displacement fields are expanded up to quadratic or higher powers of the thickness coordinate. Notable higher order shear deformation theories include those by Vlasov, 1957; Lo et al., 1977, 1978; Reddy, 1984,1987. For instance, the displacement field for the third order theory of Reddy with transverse inextensibility is given by:

$$u(x,y,z) = u_0(x,y) + z\phi_x(x,y) + z^3\left(\frac{-4}{3h^2}\right)\left(\phi_x + \frac{\partial w_o}{\partial x}\right)$$

$$v(x,y,z) = v_0(x,y) + z\phi_y(x,y) + z^3\left(\frac{-4}{3h^2}\right)\left(\phi_y + \frac{\partial w_o}{\partial y}\right) \tag{2.4}$$

$$w(x,y,z) = w_0(x,y)$$

where h is the plate thickness. This displacement field accommodates quadratic variation of the transverse shear strains (and hence stresses) and vanishing of transverse shear stresses and strains at the top and bottom of the laminate (Reddy, 1996, Oocha and Reddy, 1992).

2.2.2 Layerwise (LW) 2-D theories

The equivalent single layer theories (ESL) are adequate when the main emphasis of an analysis is to determine the overall global response of the laminated composite component, for example, gross deflections, critical buckling loads, fundamental frequencies, and associated mode shapes. However, the ESL theories tend to be inadequate for accurate assessment of localized regions, having stress concentrations or delaminations, because damage assessment of these regions require accurate prediction and assessment of 3-D state of stress and straining at the ply level (Reddy, 1996). The ESL theories are also inadequate for primary structures which tend to have thicker components, and the ESL theories do not provide accurate results with dissimilar materials (Bose and Reddy, 1998). The layerwise theories, which contain full 3-D kinematics and constitutive relations, were developed to alleviate the problems associated with the use of the ESL theories. In these theories, piecewise continuous functions are used to approximate the displacement field across the laminate thickness for displacement based approaches. It is assumed that the displacements exhibit only C^o continuity through the thickness. Even though the displacements are continuous across the thickness, their derivatives to be discontinuous, thereby allowing the possibility for the transverse (through-thickness) stress components may be continuous at interfaces separating dissimilar materials, which is the real situation, as illustrated in Figure 2.2. Furthermore, the layerwise displacement field provides a more kinematically feasible representation

of cross-sectional warping associated with thick laminates (Reddy, 1996).

Several layerwise theories have been presented by various researchers and an excellent discussion of these theories have been presented by Reddy, 1996. The theories include those based on displacement, stress or hybrid displacement. Stress formulations involving linear, quadratic or cubic functions for representing the through-the-thickness displacement stress variables. In the layerwise theory of Reddy, the displacement field in the *k*th layer is written as:

$$
\begin{aligned}
u^k(x,y,z) &= \sum_{j=1}^{m} u_j^k(x,y)\phi_j^k(z) \\
v^k(x,y,z) &= \sum_{j=1}^{m} v_j^k(x,y)\phi_j^k(z) \\
w^k(x,y,z) &= \sum_{j=1}^{n} w_j^k(x,y)\varphi_j^k(z)
\end{aligned}
\tag{2.6}
$$

where u^k, v^k, and w^k represent the total displacement components in the x, y, and z directions, respectively, of a material point initially located at (x, y, z) in the undeformed laminate, and $\phi_j^k(z)$ and $\varphi_j^k(z)$ are continuous functions of the thickness coordinate z. In general, $\varphi^k \neq \phi^k$ and both functions are chosen to be layerwise continuous. This represents a full layerwise theory in that both the in-plane and out-of-plane displacements use layerwise expansions. Theories that use layerwise expansions of the in-plane displacements are called partial layerwise theories. Figure 2.3 shows the representation of displacement across the laminate thickness. The degree of displacement variation is obtained by h-refinement (adding more subdivisions) or p-refinement (using higher order functions). The number of subdivisions through the thickness can be greater than, equal to, or less than the number of layers. With reference to Figure 2.3, the total displacement field of the laminate is given by Reddy, 1996 as

$$
\begin{aligned}
u(x,y,z,t) &= \sum_{I=1}^{N} U_I(x,y,t)\Phi^I(z) \\
v(x,y,z,t) &= \sum_{I=1}^{N} V_I(x,y,t)\Phi^I(z) \\
w(x,y,z,t) &= \sum_{I=1}^{M} W_I(x,y,t)\Psi^I(z)
\end{aligned}
\tag{2.7}
$$

where (U_I, V_I, W_I) denote the nodal values of (u, v, w), N is the number of nodes and Φ^I are the *global* interpolation functions (see Figure 2.3) for the discretization of the in-plane displacements through the thickness, and M is the number of nodes and Ψ^I are the global interpolation functions for discretization of the transverse displacement through the thickness. Further details on this theory can be found in Reddy 1996, 1998. Performance of finite elements based on the layerwise theories are discussed in Section 2.5.

2.2.3 Continuum Based 3-D and 2-D Theories

The continuum based theories are based on Vlasov's (1957) 3-D elasticity solution for simply supported isotropic plates. Applications of the method for bending, vibration and stability analysis of laminated composite plates have been presented by several investigators, (eg: Pagano 1970). Finite element 3-D models have also been developed but these are generally very cumbersome, especially for transient nonlinear problems (Bose and Reddy, 1998). However, they are useful for checking the accuracy of the solutions obtained from less rigorous theories.

The 2-D continuum theories are obtained as degenerations of the 3-D continuum theories by imposing two constraints on the 3-D theories. These constraints include: (i) a straight line normal to the mid surface before deformation remains straight but not normal after deformation, and (ii) the transverse normal components of stress and strain are negligible. Finite elements based on this degenerate continuum theory offer more generality and can accommodate full geometric nonlinearity in contrast with those based on shell theories (Reddy, 1989).

2.2.4 Sandwich Plate Theories

Sandwich construction is a special class of laminates where the inner layers are often thicker and composed of more flexible materials. Much of the earlier works focused on sandwich structures with isotropic sheets. However, in recent studies sandwich panels with composite face sheets are now being considered (or used) for aerospace, space and marine applications. The most commonly used core configurations are:

(i) Cellular cores, such as balsa wood and plastic foams, which are commonly used in marine applications,
(ii) Corrugated cores, such as cardboard; and
(iii) Honeycomb core, which are manufactured from a range of materials such as aluminum, titanium or fiber reinforced plastic in hexagonal, or square cell configuration. These cores are widely used in aerospace structures (Burton and Noor, 1997).

Sandwich construction is efficient for sustaining bending loads, but exacts a toll because of increased transverse shear flexibility and increased susceptability to local buckling of the thin outer layers.

Many finite element models have been proposed for sandwich plates. These models fall into two categories, namely, the displacement based and hybrid approaches. Review studies, such as those by Ha 1990, Mallikarjuna and Kant, 1993, and Burton and Noor, 1997, have appeared in the open literature. The computational effort associated with detailed finite element models of sandwich panels with honeycomb or corrugated cores increases with an increase in the number of cells in the core. Thus, the analysis of sandwich panels is usually carried out by replacing the core structure with an equivalent continuum layer. Various experimental and analytical techniques for predicting the effective in-plane, transverse shear, and transverse normal properties of sandwich cores, in terms of their geometry and material characteristics, have been discussed by Burton and Noor, 1997, who applied these to develop finite element models for sandwich panels. In their study, Mallikarjuna and Kant, 1993, concluded that computations involving higher-order theories showed considerable warping of the transverse cross-section of composite sandwich laminates, advocating that such behaviours cannot be correctly modelled by the first order shear deformation

theory. They also suggested that refined higher-order displacement models based on C° elements be used for finite element modeling of sandwich laminates. Thus, the layerwise theories discussed in Section 2.2.2 are considered to be well suited for modeling the behaviour of sandwich panels.

2.3 Constitutive Relations and Failure Theories for Composites

2.3.1 Linear Elastic Constitutive Relations

Most studies on composite analysis consider linear elastic constitutive relations based on the generalized Hooke's law. In formulating the constitutive relations, it is further assumed that the composite lamina is a continuum, with no gaps or empty spaces.

Let $\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{23}, \sigma_{13}, \sigma_{12}$ to be the stress components in the material principal direction; ε_{11}, ε_{22}, ε_{33}, ε_{23}, ε_{13}, ε_{12} be the corresponding strain components. The linear constitutive equations for the k-th orthotropic lamina, in material principal directions, are given by

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{Bmatrix} \tag{2.8}$$

where C_{11}, C_{12}, …, C_{66} are the elastic coefficients related to the nine independent orthotropic elastic constants, namely

E_{11}, E_{22}, E_{33}- the Young's moduli in the 1, 2, and 3 directions respectively,
ν_{12}, ν_{23}, ν_{13} – Poisson's ratio in the 1-2, 2-3 and 1-3 planes respectively, and
G_{12}, G_{23}, G_{13} – shear moduli in the 1-2, 2-3 and 1-3 planes, respectively.

Detailed expressions for the elastic coefficients are provided in Appendix A.

In general, the material principal directions do not coincide with the problem or laminate

co-ordinate system. Figure 2.4 shows a schematic representation of the relationship between the material principal axes (x_1, x_2, x_3) and the problem (global or laminate) coordinate directions (x, y, z), such that the material axes (x_1, x_2, x_3) are obtained from the global axes (x, y, z) by rotating the x-y plane counter clockwise (when looking down on the lamina) by an angle θ about the z-axis:

$$\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & \theta \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} \tag{2.9}$$

By coordinate transformations, the stress components $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{yz}, \sigma_{xz}, \sigma_{xy}$ in the global coordinates can be related to the stress in material directions by the following relation:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & 0 & 0 & 0 & -2mn \\ n^2 & m^2 & 0 & 0 & 0 & 2mn \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m & n & 0 \\ 0 & 0 & 0 & -n & m & 0 \\ mn & -mn & 0 & 0 & 0 & m^2 - n^2 \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} \tag{2.10}$$

where m=cosθ, n=sinθ.

Thus, the stress-strain relations in the global coordinates can be expressed in matrix form as

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} \overline{C}_{11} & \overline{C}_{12} & \overline{C}_{13} & 0 & 0 & \overline{C}_{16} \\ \overline{C}_{12} & \overline{C}_{22} & \overline{C}_{23} & 0 & 0 & \overline{C}_{26} \\ \overline{C}_{13} & \overline{C}_{23} & \overline{C}_{33} & 0 & 0 & \overline{C}_{36} \\ 0 & 0 & 0 & \overline{C}_{44} & \overline{C}_{45} & 0 \\ 0 & 0 & 0 & \overline{C}_{45} & \overline{C}_{55} & 0 \\ \overline{C}_{16} & \overline{C}_{26} & \overline{C}_{36} & 0 & 0 & \overline{C}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ 2\varepsilon_{yz} \\ 2\varepsilon_{xz} \\ 2\varepsilon_{xy} \end{Bmatrix} \tag{2.11}$$

where the components $\overline{C}_{ij}$ of matrix $[\overline{C}]$ are the transformed elastic coefficients referred to the (x, y, z) coordinate system. The coefficients appearing in Equation 2.11 can be found in Jones 1975 or

Reddy 1996, 1998. For the sake of completeness, they are presented in Appendix A for the plane-stress orthotropic case.

2.3.2 Composites Failure Criteria

During its service life, a laminated composite structure may be subjected to adverse loading and environmental conditions that can cause damage in the structure. The damage in the structure can be in the form of matrix cracks, fiber fracture, fiber-matrix debonds and delaminations. As these damages can result in loss of structural integrity (loss of stiffness and strength), it is essential to have a means of predicting the initiation and evolution of damage, so as to determine the structure's load carrying capacity and service life.

To model initiation and progression of damage adequately requires the analysis to be carried out at both the micro- and macro-levels. However, the different geometric scales involved poses some difficulty in the mathematical modeling of the damage and damage process. Consequently, much of the research in this area has been directed at an isolated damage mode, and a review of some of these studies has been presented by Ochoa and Reddy, 1992. When the objective is to predict failure behaviour of a laminated composite, the most practical and common approach is to use a macro-level analysis. Using this approach, several theories or failure criteria have been developed to predict the onset and progression of failure (Ochoa and Reddy, 1992, Jones, 1975). These failure criteria can be classified into two groups, namely:

(i) Independent or non-interactive failure criteria, such as maximum stress and maximum strain; and
(ii) Polynomial or interactive failure criteria, such as Tsai-Hill, Tsai-Wu and Hoffman.

These are described below.

2.3.2.1 Independent or Non-interactive Failure Criteria

The independent or non-interactive failure criteria include the maximum stress and maximum strain criteria. In the maximum stress criterion, failure is assumed to occur if any of the following conditions holds:

$$\begin{aligned} &\frac{\sigma_{11}}{X_T} \geq 1; \quad \frac{\sigma_{22}}{Y_T} \geq 1; \quad \frac{\sigma_{33}}{Z_T} \geq 1 \\ &\frac{\sigma_{23}}{R} \geq 1; \quad \frac{\sigma_{13}}{S} \geq 1; \quad \frac{\sigma_{12}}{T} \geq 1 \end{aligned} \tag{2.12}$$

where (X_T, Y_T, Z_T) are the lamina normal strengths in tension along the (1, 2, 3) material principal directions, (R, S, T) are the shear strengths in the (2-3, 1-3, 1-2) planes, respectively. When the normal stresses $(\sigma_{11}, \sigma_{22}, \sigma_{33})$ are compressive, the compressive strengths (X_C, Y_C, Z_C) are used instead of the tensile strengths in the first of equations 2.12.

In the maximum strain criterion, failure occurs if any of the following conditions hold:

$$\begin{aligned} &\frac{\varepsilon_{11}}{X_{\varepsilon T}} \geq 1; \quad \frac{\varepsilon_{22}}{Y_{\varepsilon T}} \geq 1; \quad \frac{\varepsilon_{33}}{Z_{\varepsilon T}} \geq 1 \\ &\frac{\varepsilon_{23}}{R_\varepsilon} \geq 1; \quad \frac{\varepsilon_{13}}{S_\varepsilon} \geq 1; \quad \frac{\varepsilon_{12}}{T_\varepsilon} \geq 1 \end{aligned} \tag{2.13}$$

where $\left(X_{\varepsilon T}, Y_{\varepsilon T}, Z_{\varepsilon T} \right)$ are the lamina strain capacities in tension in the (1, 2, 3) material principal directions, $(R_\varepsilon, S_\varepsilon, T_\varepsilon)$ are the shear strain capacities in the (2-3, 1-3, 1-2) planes, respectively. Again, when the normal strains $(\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33})$ are compressive, then the strain capacities in compression $(X_{\varepsilon C}, Y_{\varepsilon C}, Z_{\varepsilon C})$ respectively, are used in the first of equations 2.13, instead of the strain limit in tension.

2.3.2.2 Polynomial or Interactive Failure Criteria

All polynomial (or interactive) failure criteria are degenerate cases of the general polynomial failure criterion proposed by Tsai (Ochoa and Reddy, 1992, Jones, 1975), which is expressed as

$$F_i,\sigma_i,+F_{ij}\sigma_i\sigma_j+F_{ijk}\sigma_i\sigma_j\sigma_k+\ldots\geq 1 \tag{2.14}$$

where σ_i (i=1, 2, …,6) are the stress components in the principal material directions, F_i, F_{ij}, F_{ijk} (i, j, k = 1, 2, …, 6) are failure parameters depending on the material strength properties. The most common polynomial failure criteria are the Tsai-Wu, Hoffman and Tsai-Hill criteria. The Tsai-Wu criterion is given by

$$F_i\sigma_i+F_{ij}\sigma_i\sigma_j\geq 1 \tag{2.15}$$

where :

$$\begin{gathered}
\sigma_i(i=1,2,\ldots,6)=\sigma_{11},\sigma_{22},\sigma_{33},\sigma_{23},\sigma_{13},\sigma_{12}\\
F_1\frac{1}{X_T}-\frac{1}{X_C};\ F_2=\frac{1}{Y_T}-\frac{1}{Y_C};\ F_3=\frac{1}{Z_T}-\frac{1}{Z_C};\\
F_{11}=\frac{1}{X_TX_C};\ F_{22}=\frac{1}{Y_TY_C};\ F_{33}=\frac{1}{Z_TZ_C};\\
F_{44}=\frac{1}{R^2};\ F_{55}=\frac{1}{S_2};\ F_{66}=\frac{1}{T^2};\\
F_{12}=-\frac{1}{2}\frac{1}{\sqrt{X_TX_CY_TY_C}};\\
F_{13}=-\frac{1}{2}\frac{1}{\sqrt{X_TX_CZ_TZ_C}};\\
F_{23}=-\frac{1}{2}\frac{1}{\sqrt{Y_TY_CZ_TZ_C}}
\end{gathered} \tag{2.16}$$

In the Tsai-Hill criterion, the linear terms of the stress components do not appear, (hence F_1=F_2=F_3=0. Also, the tensile and compressive strengths are assumed to be equal. Therefore, the criterion is expressed as

$$F_{11}\sigma_{11}^2+F_{22}\sigma_{22}^2+F_{33}\sigma_{33}^2+F_{12}\sigma_{11}\sigma_{22}+F_{23}\sigma_{22}\sigma_{33}+F_{13}\sigma_{11}\sigma_{33}+F_{44}\sigma_{23}^2+F_{55}\sigma_{13}^2+F_{66}\sigma_{12}^2\geq 1 \tag{2.17}$$

where

$$
\begin{aligned}
&F_{11} = \frac{1}{X^2};\ F_{22} = \frac{1}{Y^2};\ F_{33} = \frac{1}{Z^2};\\
&F_{44} = \frac{1}{R^2};\ F_{55} = \frac{1}{S^2};\ F_{66} = \frac{1}{T^2};\\
&F_{12} = -\frac{1}{2}\left(\frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2}\right);\\
&F_{13} = -\frac{1}{2}\left(\frac{1}{Z^2} + \frac{1}{X^2} - \frac{1}{Y^2}\right);\\
&F_{23} = -\frac{1}{2}\left(\frac{1}{Y^2} + \frac{1}{Z^2} - \frac{1}{X^2}\right)
\end{aligned}
\tag{2.18}
$$

The Hoffman's criterion is similar to the Tsai-Hill criterion, except that in the Hoffman's criterion, the compressive strengths are not equal to the tensile strengths. The criterion is expressed as

$$
\begin{gathered}
F_1\sigma_{11} + F_2\sigma_{22} + F\,\sigma_{33} + \\
F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{33}\sigma_{33}^2 + F_{12}\sigma_{11}\sigma_{22} + F_{23}\sigma_{22}\sigma_{33} + F_{13}\sigma_{11}\sigma_{33} + F_{44}\sigma_{23}^2 + F_{55}\sigma_{13}^2 + F_{66}\sigma_{12}^2 \geq 1
\end{gathered}
\tag{2.19}
$$

where

$$
\begin{aligned}
&F_1 = \frac{1}{X_T} - \frac{1}{X_C};\ F_2 = \frac{1}{Y_T} - \frac{1}{Y_C};\ F_3 = \frac{1}{Z_T} - \frac{1}{Z_C}\\
&F_{11} = \frac{1}{X_T X_C};\ F_{22} = \frac{1}{Y_T Y_C};\ F_{33} = \frac{1}{Z_T Z_C};\\
&F_{44} = \frac{1}{R^2};\ F_{55} = \frac{1}{S^2};\ F_{66} = \frac{1}{T^2};\\
&F_{12} = -\frac{1}{2}\left(\frac{1}{X_T X_C} + \frac{1}{Y_T Y_C} - \frac{1}{Z_T Z_C}\right);\\
&F_{13} = -\frac{1}{2}\left(\frac{1}{X_T X_C} + \frac{1}{Z_T Z_C} - \frac{1}{Y_T Y_C}\right);\\
&F_{23} = -\frac{1}{2}\left(\frac{1}{Z_T Z_C} + \frac{1}{Y_T Y_C} - \frac{1}{X_T X_C}\right)
\end{aligned}
\tag{2.20}
$$

The failure models assume that in the post-failure regime a lamina behaves in an ideally brittle manner and the dominant stiffness and stress components reduce to zero instantaneously. This

idealization ignores the constraints imposed on the failed lamina by adjacent laminae. To model the real situation, progressive failure approaches (Chang and Chang, 1987) are used. In these approaches, if failure occurs at any point in a lamina, the stiffness of that lamina is reduced to a predetermined value, and the analysis proceeds until all laminae have failed and the laminate can sustain no additional load.

2.3.3 Nonlinear Constitutive Relations

The progressive failure method by Cheng and Chang, 1987, mentioned in Section 2.3.2 is based on piecewise linear elastic constitutive relations. Some attempts have been made to develop and/or apply nonlinear constitutive relations to accurately model the post failure behaviour of laminated composite structures. For instance, Tsujimoto and Wilson (1986) applied an elastic perfectly plastic failure analysis to predict bearing failures in composite bonded joints. Their analysis was based on Hill's yield criterion for orthotropic materials. Following standard plasticity models for metals, the incremental elasto-plastic stress-strain relations were expressed as

$$\{d\sigma\} = [D^{ep}]\{d\varepsilon\} \tag{2.21}$$

where

$$[D^{ep}] = \frac{[D^e] - [D^e]\{a\}^T[D^e]}{H + \{a\}^T [D^e\{a\}]} \tag{2.22}$$

where $[D^e]$ is the matrix of orthotropic elastic constants, $[D^{ep}]$ is the elastic-plastic matrix, {a} is the flow vector, based on Hill's yield criterion in each layer, and H is the hardening scalar function (= 0 for perfect plasticity). The authors concluded that the method provided valuable insights concerning the mechanisms of bolted joints, but did not offer significant improvement in accuracy for ultimate strength prediction, when compared to elastic analysis. However, approaches similar to this have recently been used to predict the behaviour of laminated composites (Vaziri, 1989).

In a recent study, Williams and Vaziri 1995, discussed the implementation of the so called MLT nonlinear constitutive relations developed at the University of California, Berkeley, in the LS-DYNA3D finite element code (Hallquist, 1993) for studying the impact behaviour of composite

structures. This model considered a strain softening behaviour in the past failure region. The MTL model was shown to be versatile and provided better results than the Chang and Chang (1987) method, when compared to results of impact tests. However, its usefulness is limited by the lack of standard test procedures for characterizing the strain softening behaviour.

2.4 Finite Elements for Modeling Composites

Numerous finite elements have been proposed for modelling composite structures and excellent presentations of the subject of finite element analysis of composite laminates can be found in several review studies such as Mallikarjuna and Kant 1993, Noor and Burton, 1990, Reddy 1993, and in standard texts, such as Ochoa and Reddy 1992, Reddy 1996. It is well known that the development of finite element model equations involves two main steps, namely, (i) the construction of the weighted-integral statements of the equations and (ii) the approximation of the displacements (and/or stresses), which are substituted into the weighted integral statements to obtain the algebraic equations relating the dependent and independent variables. The weighted-integral statement is derived either directly from the governing equations or from the principle of virtual displacement (or work). These approaches result in the weak form of the weighted-integral statements, which requires weaker continuity of the dependent variables, than the original differential equations (see Ochoa and Reddy, 1992 for details). In the following, interpolation functions and element types used for modelling composite structures are discussed.

Several types of finite element models are available for modelling composite structures. These include (i) the displacement models; and (ii) the mixed or hybrid models. The displacement models are the most popular ones. In these methods, the governing equations are expressed in terms of displacements, whereas in the mixed methods both displacement and stresses are independently approximated. Most commercial finite element packages utilize the displacement based approach, and the following discussion will focus mostly on displacement based approaches.

In the displacement-based methods, the displacement components (u,v,w) are approximated over an element by interpolations of the form

$$
\begin{aligned}
& u \sum_{j=1}^{n} u_j N_j^u \\
& v \sum_{j=1}^{n} v_j N_j^v \\
& w \sum_{j=1}^{n} w_j N_j^w
\end{aligned}
\tag{2.23}
$$

where u_j, v_j, w_j are the values of the generalized displacements (which includes displacements, rotations, twists, etc., as the case may be), N_j^u, N_j^v, N_j^w are the interpolation shape functions for the *u, v, w* generalized displacements, and *n* is the number of nodes associated with the element. Two basic types of interpolation functions are used for the shape functions N_j^u, N_j^v, N_j^w. These are the Lagrange and Hermite interpolation functions. For the Lagrange elements, only the function approximated is interpolated, whereas, for the Hermite elements, both the function and its derivatives are interpolated. The Lagrange type elements are C° elements and the Hermite type are C^m compatible elements, where m>0 is the order of the derivatives in the interpolation. Table 2.1 shows the interpolation functions of typical Lagrange elements with triangular or quadrilateral shapes. The table also contains an 8-node serendipity Lagrange elements, which is an incomplete form of the 9-node Lagrange element, that has proven to be effective for practical applications. The table also shows the Hermite interpolation functions of a conforming 4-node quadrilateral plate element. This element has four degrees-of-freedom $w, \partial w/\partial x, \partial w/\partial x, \partial^2 w/\partial x\partial y$ at each node for modelling the out-of-plane bending response. A non-conforming version of this element (with only three variables $w, \partial w/\partial x, \partial w/\partial x$ per node) is also widely used for laminate plate bending (Reddy 1998).

For modelling structures based on the Classical Laminate Plate Theory (CLPT), the in-plane displacements *(u,v)* are approximated by Lagrange interpolation functions and the out-of-place displacement *w*, is approximated using Hermite interpolation functions. This is because in the CLPT, the weak form of the weighted integral contains only first derivatives of *u* and *v;* and second derivatives of *w*. However, for analysis based on the First order Shear Deformation Theory (FSDT), all of the variables, $(u, v, w, \phi_1, \phi_2)$ are approximated using Lagrange interpolation functions because only first derivatives of the variables are present in the weak form of the weighted integral.

For the Higher Order Shear Theory (HOST), (eg. third order, shear deformation TSDT) the weighted integral contains first derivatives of $(u, v, w, \phi_1, \phi_2)$ and second derivatives of *w*. Hence, analysis based on the third order shear deformation theory use Lagrange functions for $(u, v, w, \phi_1, \phi_2)$ and Hermite functions for *w*, as described for the CLPT. Similarly, layerwise theory requires only C^o continuity of the displacements across element (or layer) boundaries. Hence, Lagrange functions are used to approximate the variables. This is also true for the conventional 3-D finite element, since the 3-D and 2-D layerwise theories are essentially the same (Reddy 1996). For instance, a 4-node Lagrange quadrilateral element with a linear interpolation is similar to an 8-node linear solid element.

The VAST finite element program contains two doubly-curved multi-layered shell elements. One of the elements is based on the Equivalent Single Layer (ESL) higher order theory and the other is based on a layer-wise first-order shear deformation theory. The ESL element is based on the 8-node degenerated 3-D shell element (see Bathe 1982). It allows the use of up to 8^{th} order higher-order displacement terms and the FOST theory can be obtained as a special case. For the element based on the layer-wise theory, each layer is treated as a standard 8-node isoparametric shell element, as discussed in Section 2.2.2. This element can allow up to six layers and includes many of the available layerwise theories as special cases. Details of the element formulations can be found in Jiang and Chernuka (1996).

2.5 Applications and Assessment of FE Formulations for Composites

2.5.1. Introduction

The finite elements discussed in Section 2.4 have been used in conjunction with the various composite theories presented in Sections 2.2 and 2.3 to model the static, free vibration, buckling, transient and nonlinear behaviour of composite structures. The performance of the various finite element theories in these applications have been widely discussed by many investigators (eg., Ochoa and Reddy 1992, Reddy 1996, Mallikarjuna and Kant 1993, and Noor and Burton, 1990). In this section, a summary of the applications is provided to highlight issues

such as accuracy, convergence rate, and sensitivity to locking, that are associated with the use of the various finite element theories. The summary is presented according to the types of applications below.

2.5.2 Static Analyses

ESL Solutions

Static analysis involving the computation of static displacements and stresses have been performed using the various ESL and layerwise theories. To assess the performance of the elements, consider an all-round simply supported square plate subjected to a sinusoidal load of intensity q_o that was first considered by Ochoa and Reddy 1992, and Reddy 1996. The plate was made of anti-symmetric cross ply or angle ply laminate, and had the following material properties: $E_{11}/E_{22} = 25$, $G_{12} = G_{13} = 0.5E_{22}$, $G_{23} = 0.2E_{22}$, $\nu_{12} = \nu_{13} = \nu_{23} = 0.25$, $E_{11} = 172GPa$, $G_{12} = 3.5GPa$. A comparison of the performance of the Classical Laminate Plate Theory (CLPT), the First order Shear Deformation Theory FSDT, and the Third order Shear Deformation Theory (TSDT) was made by Ochoa and Reddy 1992; and Reddy 1996. For the CLPT, a 4x4 mesh of 4-node conforming (Hermite) elements were used to model a quarter of the plate. For the FSDT, a 2x2 mesh of 9-node quadratic (Lagrange) elements were used to model a quarter of the plate. A shear correction factor of 5/6 was used for the FSDT-based element. For the TSDT, a 2x2 mesh of 4-node Hermite conforming elements was used to model a quarter of the structure. Two types of symmetry boundary conditions, designated as SS-1 and SS-2 in Figure 2.5 were used. Table 2.2 shows the finite element displacement and stress responses provided the CLPT and FSDT for various side length to thickness (a/h) ratios and number of plies. It is seen that the finite element responses agree well with the analytical solutions (shown in parentheses). However, in general, the CLPT under-predicts the deflections and stresses. For the thicker plate configurations (a/h=5) it is seen the stresses predicted by the CLPT and FSDT deviate significantly from those predicted by the TSDT, which is considered more accurate for such configurations.

Several investigators have stressed the need to use appropriate boundary conditions for the quarter plate model. For instance, Ochoa and Reddy, 1992, and Reddy 1996, have shown that

the SS1 and SS2 boundary conditions were the correct quarter model boundary conditions for plates with cross-ply $(0/90/\ldots)_{even}$ and angle-ply $(2/-2/\ldots)_{even}$ laminates, respectively. They showed that the use of SS2 for the cross-ply and SS1 for the angle-ply could lead to erroneous results. However, this discrepancy reduces as the number of layers increases. This is because the non-zero bending-stretching coupling matrix coefficients (B_{ij}) become smaller as the number of layers is increased.

Layerwise Element Solutions

The performance of layerwise finite elements in static analysis have also been discussed by several researchers. To illustrate the behaviour of layerwise elements in bending analysis, consider a square, simply supported, symmetric cross-ply (0/90/0) laminated plate subjected to a sinusoidally distributed transverse load on the upper surface of the plate (see Reddy 1996). The material properties of the laminate are $E_{11} = 172GPa$, $E_{22} = E_{33} = 6.9GPa$ $G_{12} = 3.5Gpa$ $G_{13} = G_{23} = 1.38GPa$, $\nu_{12} = \nu_{13} = \nu_{23} = 0.25$. The following layerwise finite element meshes were used to model one-quarter of the plate. The meshes are:

i. A 6x6 mesh of 4-node linear Lagrange elements with six linear subdivisions through the thickness. This mesh is designated as E4-L6;
ii. A 3x3 mesh of 8-node serendipity quadratic Lagrange elements with three quadratic subdivisions through the thickness (designated as E8-Q3);
iii. A 3x3 mesh of 9-node quadratic Lagrange elements with three quadratic subdivisions through the thickness (designates as E9-Q3);
iv. A 2x2 mesh of 12-node serendipity cubic Lagrange elements with three quadratic subdivisions through the thickness (designated E12-Q3); and
v. A 2x2 mesh of 16-node cubic Lagrange elements with three quadratic subdivisions through the thickness (designated as E16-Q3).

Table 2.3 shows the responses obtained using these elements for plates with various a/h ratios, with full or selectively reduced integration of the element equations. All meshes provided reasonably close responses, especially for the thicker plates (a/h=4). When full integration was used all elements except the cubic Lagrange element (E16-Q3) exhibited a noticeable amount of shear locking. This spurious mode was significantly reduced by using the selectively reduced integration scheme, in which all element stiffness matrix coefficients related to the transverse shear and

transverse normal effects are computed using reduced integration. A similar trend was observed for other stress components. The exact solution used for the comparison was based on three-dimensional elasticity solution (see Reddy 1996). The ability of the layer-wise element to accurately model three-dimensional effects such as free-edge effects, which are unaccounted for by two-dimensional models was also demonstrated by Reddy 1996.

As discussed in Section 2.2, a major advantage of layerwise theories is their ability to provide more accurate stresses, compared to the ESL theories. This has been demonstrated for the VAST ESL and layered elements by Jiang and Chernuka, 1996. They considered a thick square plate, of side length 10, thickness 10. The plate consisted of four equal layers of an orthotropic material, with a laminate configuration of $\left[0^\circ / 90^\circ / 90^\circ / 0^\circ\right]$ $E_{11} = 100$, $E_{22} = 4.0$, $<_{12} = 0.25$, $G_{12} =$, $G_{13} = 2.0$, $G_{23} = 0.8$.

Figure 2.6 shows the through-the-thickness variation of the normal stress Φ_{xx} near the plate center. Results are shown for the ESL element (IEC = 27) that is based on Mindlin theory and an 11th order theory; and for the layerwise element (IEC = 28) using three and six mathematical layers through the thickness. It is seen that the ESL element based on the Mindlin theory under predicts the maximum stress. However, the ESL element based on an 11th higher order theory predicts stresses that are close to the layerwise elements solution. The figure also shows that for the layerwise theory, the stresses converge as the number of mathematical layers increases from three to six layers Reddy, 1996, has also shown that the stress predictions layerwise elements closely approximate those based on 3-D elasticity solutions.

Continuum Element Solutions

The behaviour of the continuum based elements have been investigated by Ochoa and Reddy 1992. An 8-node quadrilateral element designated as QHD40 (having seven degrees-of-freedom at the corner nodes $(u, v, w, \theta_1 \theta_2, \phi_1 \phi_2)$ and three degrees-of-freedom at the mid-side nodes (w, θ_1, θ_2) was used to model a simply supported rectangular (0/90/0) laminate, with the following material properties: $E_{11} = E_{22} = 25$, $G_{12} = G_{23} = 2.5$, $G_{13} = G_{12}$, $v_{12} = v_{13} = 0.25$, $E_{11} = 172 GPa$. The plate was subjected to a transverse sinusoidal load. Table 2.4 shows the displacement and stress responses for laminates with various length-to-thickness ratios, in where the finite element and

solutions are compared to the elasticity and CLPT solutions. It is seen that the correlation between the finite element and elasticity solutions improves as the plate becomes thinner (larger a/h).

2.5.3 Natural Frequency and Buckling Analyses

Several studies on natural frequency and buckling analysis of composite structures by equivalent single layer (ESL) based finite elements have been presented by several investigators (Ocha and Reddy 1992, Reddy 1996, Mallikarjuna and Kant 1993). To illustrate the performance of these elements in natural frequency and buckling analysis, consider a simply supported square plate made of a /45/-45/… angle ply laminate with the following material properties: $E_{11}/E_{22} = 40$, $G_{12} = G_{13} = 0.6E_{22}$, $G_{23} = 0.5E_{22}$, $\nu_{12} = \nu_{13} = 0.25$. The natural frequency and buckling behaviour of this plate, based on the CLPT, FSDT and TSDT, have been presented by Reddy 1996. A quarter symmetry model with SS-2 boundary conditions was used in the finite element model. As before, 4-node conforming elements were used to the CPLT and TSDT (or HSDT) theories, whereas 9-node quadratic Lagrange elements were used for the FSDT. Furthermore, a shear correction factor of 5/6 was used for the FSDT. Tables 2.5 and 2.6 show the non-dimensionalized fundamental frequencies, $\bar{\varpi} = \varpi_{11}\, a^2 \left(\sqrt{\rho / E_{22}}\right)/ h$, and uniaxial buckling loads $\bar{N} = N_{cr} a^2 / \left(E_{22} h^3\right)$, respectively. The tables show that in general, the classical laminate theory (CLPT) over-predicts the frequency and buckling loads compared to the first order shear deformation theory (FSDT) and higher order shear deformation theory (HSDT or TSDT). It is shown that there is no significant difference between the predictions of the FSDT and HSDT. Thus the advantage of the HSDT over the FSDT, for these types of analysis lies in the fact that the HSDT does not require the use of shear correction factors. However, the HSDT is more computationally intensive and more difficult to implement.

2.5.4 Nonlinear Analysis

Nonlinearities in composite structures can be due to geometric or material nonlinear effects. However, the geometric nonlinear effects have received the most attention in terms of nonlinear analysis of composites. This is due to the fact that composites exhibit quite different geometric nonlinear behaviour, compared to isotropic structures. For instance, composites exhibit

nonlinear behaviour even at very small loads and deflections, depending on the lamination scheme and the boundary conditions (Ochoa and Reddy, 1992). To illustrate the nonlinear geometric behaviour of composites, we use the example of an antisymmetric cross-ply laminate (90/0) presented by Ochoa and Reddy 1992. The laminate has two opposite sides, pinned or hinged; and the other two sides free, and is subjected to a uniformly distributed transverse load. The material properties are:

$E_{11} = 150\,GPa$, $E_{22} = 9.33\,GPa$, $G_{12} = G_{13} = G_{23} = 4.66\,GPa$, $\nu_{12} = 0.3, a/b = 6, a = 225mm, h = 10mm$

The structure was analyzed by nine-node quadratic Lagrange elements based on the FSDT. Table 2.7 presents the nonlinear results for the two boundary conditions and for two cases of the load, one case in which the load is applied in the downward direction, and the other case, in which the load is applied in the upward direction. The results from a linear analysis are also shown in the table for comparison. For the hinged case, the axial force N_{11} is approximately equal to zero and hence the plate is in pure bending, and the magnitude of nonlinear displacement is independent of the loading direction. However, for the pinned case the axial force N_{11} is non-zero and hence the plate already exhibits a coupled bending-membrane behaviour prior to the application of the load. As a result, the magnitude of the nonlinear displacement is dependent on the sign of the applied load as shown in the table. The lesson to be learned from this example is that careful application of boundary conditions is required to obtain the correct nonlinear response of composite structures.

In a related study, Ochoa and Reddy (1992) have shown that the nonlinear geometric response provided by elements based on the CLPT tended to under-predict the displacement response. They have also investigated the use of nine-node and four-node continuum based elements for modelling the nonlinear behaviour of composite shell structures. Reddy 1996 has also investigated the post-buckling behaviour of composite panels, whereby the nonlinear geometric model was incorporated with a progressive failure analysis based on the maximum stress and Tsai-Wu failure criteria, using nine-node continuum based finite elements. The study showed good agreement between the finite element and experimental results.

Williams and Vaziri, 1995, have also investigated the nonlinear behaviour of composite structures. Their study involved the use of the four-noded Belytchko-Lin-Tsay (BLT) (Belytchko et

al., 1984) shell element available in the LSDYNA3D element library. This element accounts for nonlinear geometric effects, and was used in conjunction with two constitutive models: (a) the progressive damage model of Chang and Chang (1987), and (b) the elastic-brittle composite damage model by Matzenmiller et al. (1991), to model the nonlinear response of a composite plate subjected to an impact load. The analysis, which was compared to experimental results, provided an insight into the energy absorption behaviour of composites in an impact event. It is envisaged that similar analysis methodologies will be required for detailed modelling the response of composite masts to extreme loads such as blast and shock. One advantage of this model is the simplicity of modelling structures with this element and its computational efficiency, as it has only four nodes, and uses a reduced integration, (one-point integration) with hour glass control.

2.5.4 Transient Analysis

The transient dynamic response behaviour of composite structures has been reported by several investigators. For instance, Reddy 1996 has presented the nonlinear transient analysis of simply supported, cross-ply (0/90) and angle-ply (45/-45) plates, subjected to uniformly distributed transverse loads, using nine-noded quadratic elements, in which the elements were modelled with either three or five degrees-of-freedom. It was shown that the three degrees-of-freedom element provided stiffer responses than the five degrees-of-freedom element. As mentioned in Section 2.5.4, Williams and Vaziri (1995) have also investigated transient dynamic response of composites, in which geometric nonlinear effects were accounted for and progressive failure constitutive models used to model the material behaviour. Mallikarjuna and Kant 1993 have also discussed the transient response of moderately thick composite sandwich structures, using elements that were based on the FSDT as well as higher order refined theories. They showed that the FSDT under-predicted the in-plane and transverse displacements by about 50% and 70%, respectively, for moderately thick (a/h=10) composite sandwich plates; compared to results obtained using the higher order refined theories, thus illustrating the need to use elements based on higher order or layerwise theories for sandwich structures.

2.6 Discussions

Several finite element formulations for composites were reviewed in the preceding sections. The review focused mostly on kinematic theories, constitutive relations for composites, and applications of the elements for various types of analysis. The kinematic theories reviewed included the equivalent single layer (ESL) 2-D theories, layerwise (LW) 2-D theories and continuum based 3-D and 2-D theories.

The ESL theories treat the heterogenous laminated composite as a statically equivalent single layer, thereby effectively reducing the 3-D continuum to 2-D problem. Several ESL theories, including the Classical Laminate Plate Theory (CLPT), First order Shear Deformation Theory (FSDT) and higher (eg. third) order shear deformation theories (TSDT) were discussed. In general, finite elements based on these theories are simpler to formulate, and are very suitable for computing global response parameters, such as natural frequencies, buckling loads, strain energy, and deformations. However, these theories are not very suitable for accurate computation of stresses, especially at discontinuities or other local effects. For such analysis, only the ESL theories based on the higher order theories provide accurate through-the-thickness stresses, at the expense of high computational cost (see Reddy 1996, Jiang and Chernuka 1996).

The layerwise theories can provide accurate through-the-thickness stresses and are necessary for the analysis/design of critical components for which accurate knowledge of the state of stress is important. As noted above for the higher order ESL theories, the computational cost involved for analysis using layerwise theories can also be high, and hence their use should be restricted to critical components. Their use for the computation of global quantities such as strain energy, buckling loads, natural frequency and global deformation is not advocated due to the computational cost involved. It must be emphasized, however, that for moderately thick to thick sandwich structures, layerwise theories may be required even for computing global response quantities, unless higher order terms are included in the ESL theories.

Various element types based on the above theories have been used for modelling composite structures. The most common element types are:

i. Four-node conforming plate elements based on the CLPT or TSDT;
ii. Nine-node quadratic Lagrange elements based on FSDT or HSDT, or layerwise theories;
iii. Eight-node continuum based elements based on FSDT, HSDT and layerwise theories; and
iv. Four-node linear Lagrange elements based on FSDT, HSDT or layerwise theories.

These elements have several advantages, and disadvantages, which have to be considered in their use. For instance, the four-node conforming element is used mostly for analysing plate type structures. The nine-node quadratic element is very popular and can be used with several composite theories. However, the fact that it has an interior node might make its use awkward in commercial finite element codes, although, the serendipity version of the element can be used without loss of accuracy. The element locks when fully integrated for thin structures, so reduced integration has to be used for such cases. The eight-node continuum element is also very popular and is very suitable for problems with large displacements and rotations (see Jiang and Chernuka 1996). However, this element is also susceptible to locking for thin structures and may require the use of reduce integration. The four-node linear Lagrange element is very simple but susceptible to serious locking, and should be used with care for bending problem. Reduced integration, that includes hour glass control can be used to improve its accuracy. In this regard, the four-node shell element formulation by Belytschko et al. (1984) is considered to be a suitable element for composite analysis. It is accurate, economical and can accommodate large displacement, large rotations, large strains and material nonlinearities.

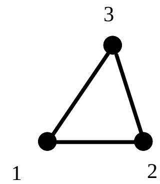
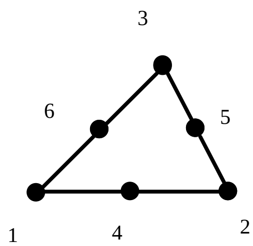
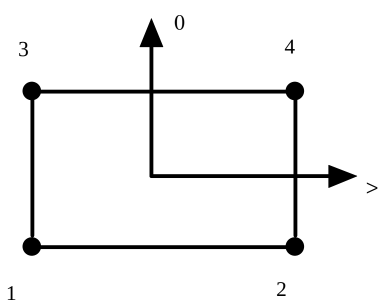
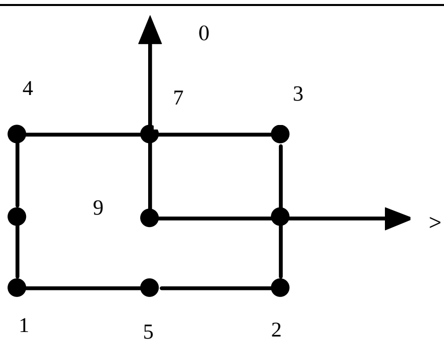
In terms of failure analysis, three approaches were reviewed:

i. First ply failure based on classical failure criteria such as maximum stress, maximum strain, Tsai-Hill, Tsai-Wu and Hoffman;
ii. Progressive failure (last ply failure) based also on the classical failure criteria (maximum stress, maximum strain, Tsai-Hill, Tsai-Wu, Hoffman);
iii. Elasto-plastic constitutive relations based on the MLT (Matzenmiller, Lubliner and Taylor, 1991) method.

Designs based on first ply failure tend to be conservative, so it is desirable to consider the past failure behaviour of composites to approximate reality. In this regard, the use of the progressive failure methodology of Chang and Chang, 1987 in combination with classical failure criteria is considered the most mature and practical approach. The elasto-plastic based approaches by

Matzenmiller et al., 1991; and Vaziri 1989 have great merit and potential. However, their use is limited by the fact that material parameters needed to completely define the models are not fully understood or characterized.

Table 2.1: Lagrange Interpolation Functions for Typical 2-D Elements (Reddy 1996)

Element Type	**Interpolation Functions**
	$N_1 = L_1$, $L_i = \dfrac{A_i}{A}$ area coordinates $N_2 = L_2$ $N_3 = L_3$
Linear triangle	
 Quadratic Triangle	$N_1 = L_1\,(2L_1 - 1)$, $N_2 = L_2\,(2L_2 - 1)$ $N_3 = L_3\,(2L_3 - 1)$, $N_4\ 4L_1L_2$ $N_5 = 4L_2L_3$, $N_6 = 4L_3L_1$ L_I = area coordinates
 Linear Quadrilateral	$N_1 = \dfrac{1}{4}$ (1->)(1-0) , $N_2 = \dfrac{1}{4}$(1+>)(1-0) $N_3 = \dfrac{1}{4}$ (1+>)(1+0) , $N_4 = \dfrac{1}{4}$(1->)(1+0)
 9-node Quadrilateral Lagrange	$\begin{Bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \\ N_6 \\ N_7 \\ N_8 \\ N_9 \end{Bmatrix} = \frac{1}{4}\begin{Bmatrix} (1-\xi)(1-\eta)(-\xi-\eta-1)+(1-\xi^2)(1-\eta^2) \\ (1+\xi)(1-\eta)(\xi-\eta-1)+(1-\xi^2)(1-\eta^2) \\ (1+\xi)(1+\eta)(\xi+\eta-1)+(1-\xi^2)(1-\eta^2) \\ (1-\xi)(1+\eta)(-\xi+\eta-1)+(1-\xi^2)(1-\eta^2) \\ 2(1-\xi^2)(1-\eta)-(1-\xi^2)\,(1-\eta^2) \\ 2(1+\xi^2)(1-\eta^2)-(1-\xi^2)\,(1-\eta^2) \\ 2(1-\xi^2)(1+\eta)-(1-\xi^2)\,(1-\eta^2) \\ 2(1-\xi)(1-\eta^2)-(1-\xi^2)\,(1-\eta^2) \\ 4(1-\xi^2)(1-\eta^2) \end{Bmatrix}$

<table>
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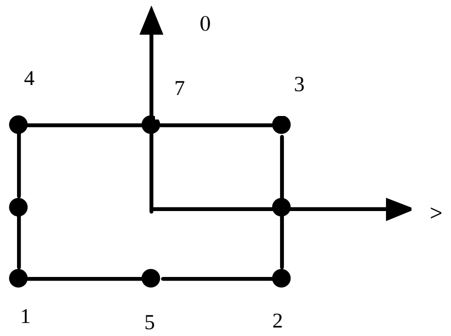

8-Noded Serendipity Lagrange
</td><td>

$$\begin{Bmatrix}N_1\\ N_2\\ N_3\\ N_4\\ N_5\\ N_6\\ N_7\\ N_8\end{Bmatrix}=\frac{1}{4}\begin{Bmatrix}(1-\xi)(1-\eta)(-\xi-\eta-1)\\ (1+\xi)(1-\eta)(\xi-\eta-1)\\ (1+\xi)(1+\eta)(\xi+\eta-1)\\ (1-\xi)(1+\eta)(-\xi+\eta-1)\\ 2(1-\xi^2)(1-\eta)\\ 2(1+\xi)(1-\eta^2)\\ 2(1-\xi^2)(1+\eta)\\ 2(1-\xi)(1-\eta^2)\end{Bmatrix}$$

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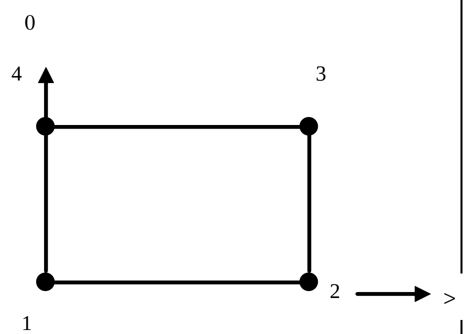

4-node Conforming Hermite
</td><td>

Hermite cubic element:

Interpolation functions for

var *iable u* $\frac{1}{16}(\xi+\xi_1)^2(\xi\xi_i-2)(\eta+\eta_i)^2(\eta\eta_i-2)$

derivative $\partial u/\partial\xi$ $-\frac{1}{16}\xi_i(\xi+\xi_1)^2(\xi\xi_i-1)(\eta+\eta_i)^2(\eta\eta_i-2)$

derivative $\partial u/\partial\eta$ $-\frac{1}{16}(\xi+\xi_1)^2(\xi\xi_i-2)\eta_i(\eta+\eta_i)^2(\eta\eta_i-1)$

derivative $\partial^2 u/\partial\xi\partial\eta$ $\frac{1}{16}\xi_i(\xi+\xi_1)^2(\xi\xi_i-1)\eta_i(\eta+\eta_i)^2(\eta\eta_i-1)$

For node j(I=1,…,4)

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Table 2.2: Comparison of Finite Element and Analytical Solutions of CLPT and FSDT for Anti-Symmetric Cross-Ply Laminated Square Plates Subjected to Sinusoidal Load (Reddy 1996)

Number of Layers	a/h	FEM Theory	$\overline{w}^*$	$\overline{\sigma}_{11}^*$	$\overline{\sigma}_{23}^*$
2	5	CLPT	1.043 (1.064)	6.659 (7.157)	
		FSDT	1.759 (1.758)	6.948 (7.157)	(2.729)
		HSDT	1.6671.667)	7.669 (8.385)	(3.155)
	10	CLPT	1.043 (1.064)	6.659 (7.157)	
		FSDT	1.238 (1.237)	6.948 (7.157)	2.652 (2.729)
		HSDT	1.214 (1.216)	6.829 (7.468)	(3.190)
10	5	CLPT	0.444 (0.442)	4.611 (5.009)	
		FSDT	1.137 (1.137)	4.864 (5.009)	(2.729)
		HSDT	1.135 (1.129)	5.762 (6.340)	(3.362)
	10	CLPT	0.444 (0.442)	4.611 (5.009)	(2.729)
		FSDT	0.616 (0.615)	4.863 (5.009)	3.408
		HSDT	0.619 (0.616)	4.842 (5.346)	
20	10	CLPT	0.444 (0.442)	4.611 (5.009)	
		FSDT	0.616 (0.615)	4.863 (5.009)	2.652 (2.729)
		HSDT			

$* \; \overline{w} = \left(wE_{22}h^3\right)10^2 / \left(a^4 q_o\right);$ $\quad \overline{\sigma}_{11} = \sigma_u\left(\frac{a}{2}, \frac{b}{2}, -\frac{h}{2}\right)h^2 - 10 / \left(a^2 q_o\right);$ $\quad \overline{\sigma}_{23} = \sigma_{23}(0{,}0{,}0)\, h - 10 / (aq_o)$

Table 2.3: Ratio of Computed Transverse Displacement to Exact Transverse Displacement and $(\sigma_{xx} / \sigma_{xx}\ exact))$ at Centre of a Square, Simply Supported (0/90/0) Laminate Under Sinusoidal Transverse Load

Mesh	Integ. Scheme	(w/exact w)			$(\sigma_{xx} / exact\ \sigma_{xx})$		
		a/h=4	a/h=20	a/h=200	a/h=4	a/h=20	a/h=200
E4-L6	Full	0.9815	0.9284	0.1280	0.9754	0.9360	0.3267
E8-Q3	Full	0.9901	0.9981	0.9807	0.9860	1.0145	1.0276
E9-Q3	Full	0.9906	0.9987	0.9845	0.9860	1.0145	1.0296
E12-Q3	Full	0.9880	0.9968	0.9615	0.9873	1.0030	1.2883
E16-Q3	Full	0.9907	1.0006	1.0001	0.9867	1.0000	1.0103
E4-L6	Reduced	0.9900	0.9945	0.9942	0.9857	0.9987	0.9990
E8-Q3	Reduced	0.9873	0.9992	0.9992	0.9861	1.0148	0.9982
E9-Q3	Reduced	0.9880	0.9998	1.0001	0.9861	1.0148	0.9970
E12-Q3	Reduced	0.9980	0.9966	0.9650	0.9873	1.0030	1.2693
E16-Q3	Reduced	0.9906	0.9997	1.0000	0.9868	1.0000	1.0000

Table 2.4: Normalized Stresses and Displacements for Simply-Supported Square (0/90/0) Laminate Under Transverse Sinusoidal Load

a/h	Approach	$\bar{\sigma}_x$ $\left(\frac{a}{2},\frac{a}{2},\pm\frac{h}{2}\right)$	$\bar{\sigma}_y$ $\left(\frac{a}{2},\frac{a}{2},\pm\frac{h}{6}\right)$	$\bar{\sigma}_{xy}$ $\left(0,0,\pm\frac{h}{2}\right)$	$\bar{\sigma}_{xz}$ $\left(0,\frac{a}{2},0\right)$	$\bar{\sigma}_{yz}$ $\left(\frac{a}{2},0,\ 0\right)$
4	FEM	0.391	0.572	0.0448	0.308	0.251
	Elasticity	0.755	0.556	0.0505	0.282	0.217
10	FEM	0.529	0.292	0.0289	0.652	0.123
	Elasticity	0.500	0.279	0.0280	0.369	0.130
		0.590	0.288	0.0289	0.357	0.123
100	FEM	0.542	0.167	0.0215	0.393	0.0827
	Elasticity	0.539	0.181	0.0213	0.395	0.0828
	CLPT	0.539	0.180	0.0213	0.395	0.0823

Table 2.5: Non-dimensionalized Fundamental Frequencies $\bar{\varpi}=\varpi_{11}\frac{a^2}{h}\sqrt{\frac{\rho}{E_2}}$, of Simply Supported (SS-2), Antisymmetric Angle=ply (45/-45/…) Square Plates (Reddy 1996)

$\frac{a}{h}$	Theory	n = 2	n = 6
4	TSDT	9.753	10.895
	FSDT	9.161	10.805
	CLPT	13.506	13.766
10	TSDT	13.536	19.025
	FSDT	13.044	19.025
	CLPT	14.439	24.611
100	TSDT	14.621	24.739
	FSDT	14.618	24.741
	CLPT	14.636	24.825

Table 2.6: Non-dimensionalized Uniaxial Buckling Loads, $\bar{N} = N_{cr}\dfrac{a^2}{E_2 h^3}$, of Simply Supported (SS-2), Antisymmetric Angle=ply (45/-45/…) Square Plates

$\dfrac{a}{h}$	Theory	n = 2	n = 6
5	TSDT	10.881	12.169
	FSDT	9.385	11.297
10	TSDT	18.154	32.405
	FSDT	17.552	32.525
20	TSDT	20.691	53.198
	FSDT	20.495	53.365
50	TSDT	21.539	60.760
	FSDT	21.505	60.798
100	TSDT	21.666	62.022
	FSDT	21.658	62.032
	CLPT	21.709	62.455

Table 2.7: Nonlinear Cylindrical Bending of a (90/0) Laminate Under Uniformly Distributed Transverse Load. (Ochoa & Reddy, 1992).

$\bar{\varpi} = w/h$					
Load P_o	Pinned Linear*	Pinned, Nonlinear		Hinged, Nonlinear	
		A - Negative Load	B - Positive Load	A - Negative Load	B - Positive Load
0.005	-0.235	-0.159	0.475	-0.429	0.429
0.01	-0.470	-0.255	0.673	-0.858	0.858
0.02	-0.940	-0.386	0.847	-1.710	1.710
0.03	-1.41	-0.480	0.954	-2.550	2.550
0.04	-1.88	-0.555	10.34	-3.370	3.370
0.05	-2.35	-0.618	1.100	-4.190	4.190
.010	-4.70	-0.845	1.327	-1.920	7.920
0.25	-11.75	-1.233	1.705	-16.16	16.16
0.50	-23.50	-1.609	2.075	-24.82	24.82
0.75	-35.25	-1.870	2.332	-30.87	30.87
1.0	-47.00	-2.078	2.532	-35.69	35.69
2.0	-94.00	-2.665	3.117	-49.56	49.56
3.0	-141.00	-3.075	6.525	-59.65	59.65
4.0	-188.00	-3.402	3.850	-68.00	68.00
5.0	-235.00	-3.675	4.125	-75.33	75.33

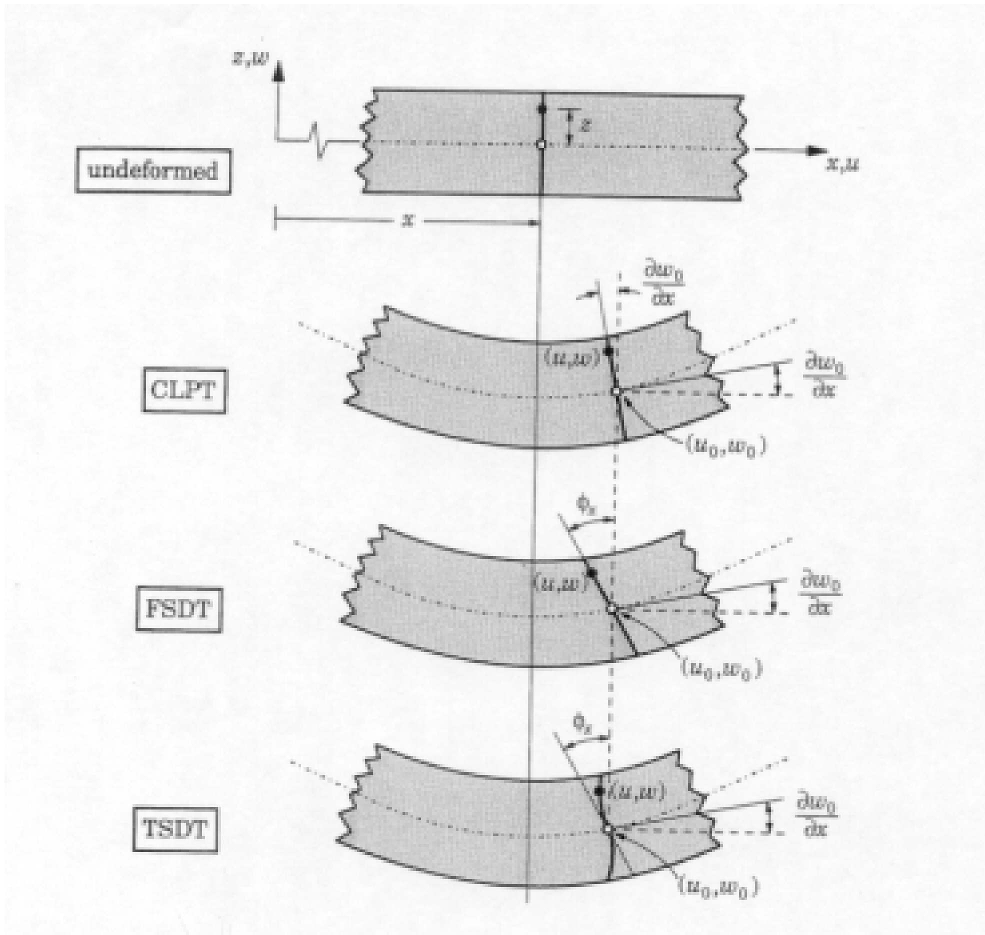


Figure 2.1: Deformation of Transverse Normals in CLPT, FSDT and TSDT (Reddy, 1996)

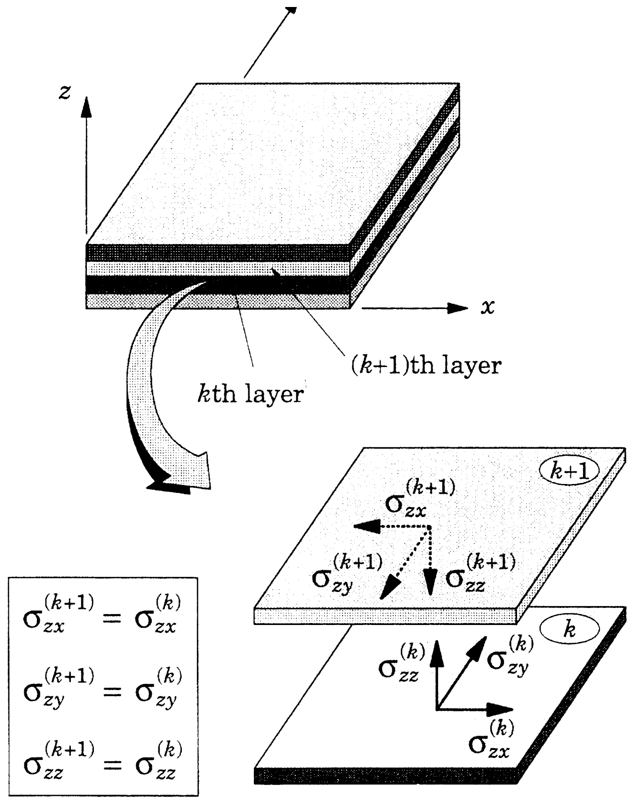


Figure 2.2: Equilibrium of Interlamina Stresses (Reddy 1996)

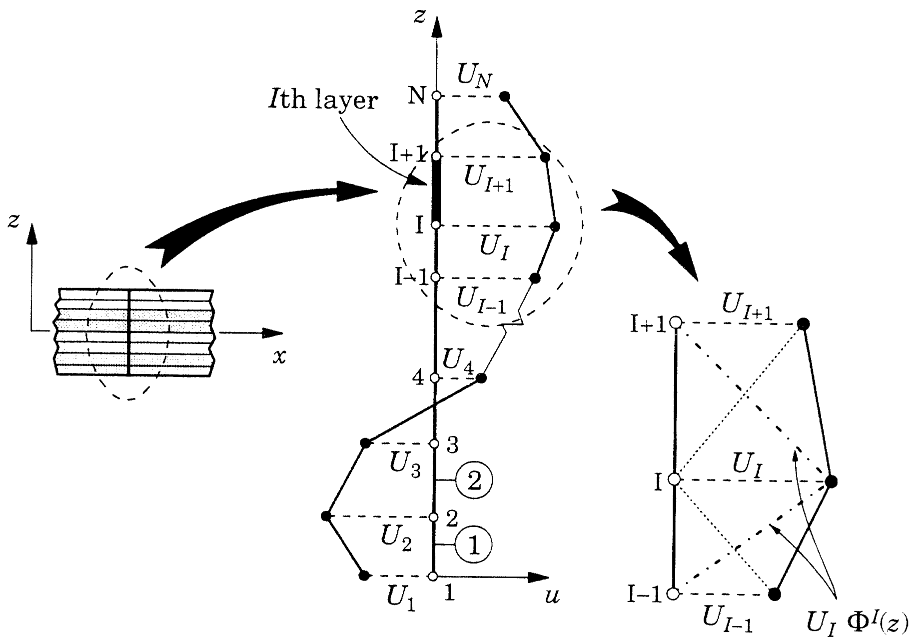


Figure 2.3: Displacement Representation in Layerwise Theory (Reddy 1996)

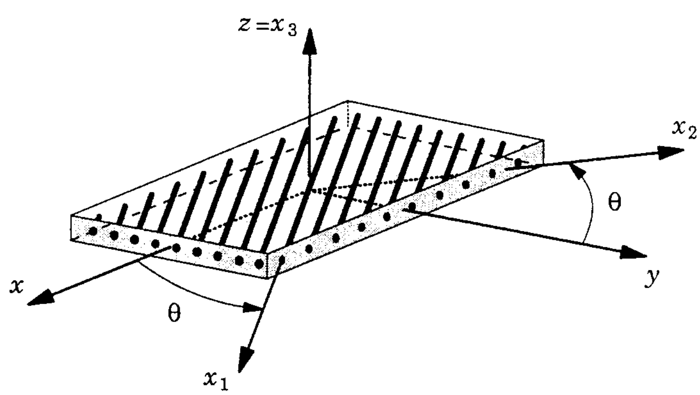
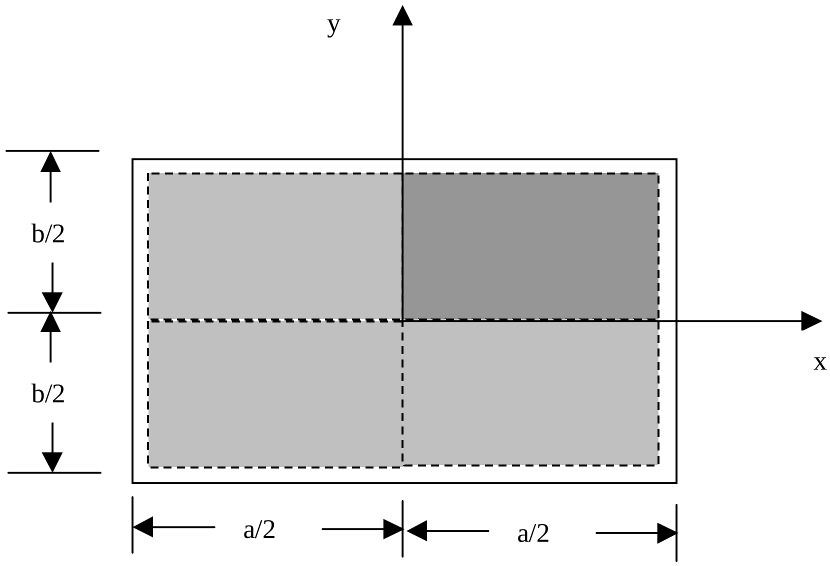


Figure 2.4: Global and Material Principal Axes of a Fiber-Reinforced Lamina (Reddy, 1996)



Theory	B.C.	$x = 0$	$y = 0$
FSDT	SS-1	$u_0 = 0 \quad \phi_x = 0$	$v_0 = 0 \quad \phi_y = 0$
	SS-2	$v_0 = 0 \quad \phi_x = 0$	$u_0 = 0 \quad \phi_y = 0$
CLPT, HSDT	SS-1	$u_0 = 0 \quad \frac{\partial w_0}{\partial x} = 0$	$v_0 = 0 \quad \frac{\partial w_0}{\partial y} = 0$
	SS-2	$v_0 = 0 \quad \frac{\partial w_0}{\partial x} = 0$	$u_0 = 0 \quad \frac{\partial w_0}{\partial y} = 0$

Figure 2.5: Symmetry Boundary Conditions for Anti-symmetric Cross-ply and Angle-ply Laminates

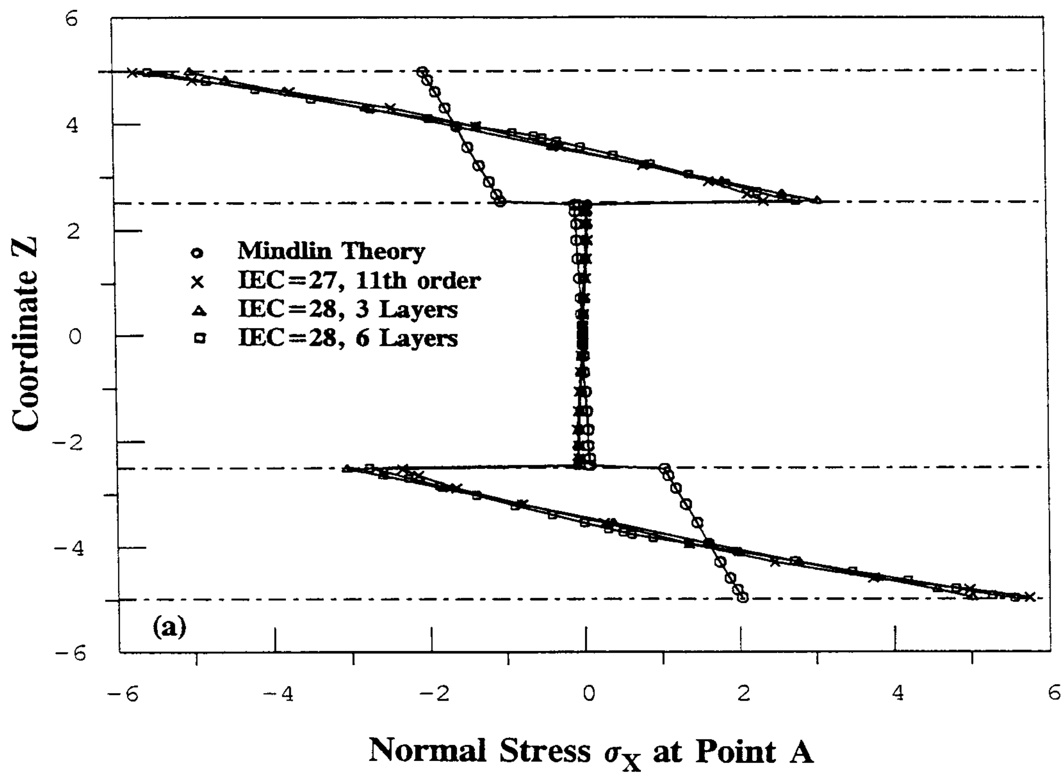


Figure 2.6: Normal Stress Φ_{xx} Near Center of Thick Orthotropic Square Plate (Jiang and Chernuka, 1996)

3 REVIEW OF MASTS

3.1 Introduction

This chapter provides a review of ship masts. The review covers metallic masts, which are the most commonly used masts on naval ships and auxiliary vessels, and composite masts, which are being evaluated or used by a few industrialized countries. The thrust of the review was to identify various metal and composite mast configurations, including the geometric and structural shapes, materials of construction, design and analysis methodologies, construction approaches, in service performance, maintenance and repair procedures. These pieces of information are required for the development of the mast software system described in Chapters 3, 4 and 5. The review of metallic masts is provided in Section 3.2, whereas Section 3.3 deals with the review of composite masts. Finally the results of the reviews are summarized in Section 3.4 in a format that can be fed directly into the development of the mast software system in Chapters 3, 4 and 5.

3.2 Metallic Masts

3.2.1 Metallic Mast Configurations

A mast is a structure consisting of a single pole or a combination of structural members that projects itself above the ship, and is used for supporting navigational and weather equipment and electronic devices such as radar antennas. Traditionally, masts have been classified into four main categories according to their configurations. These are the unstayed polemast, stayed polemast, three-legged mast and four-legged lattice mast (Liang et al. 1994). Recently, efforts are being made to develop enclosed masts constructed of metals for naval applications (Bosman 2000). The geometric configurations and applications of the various categories of masts are described below.

3.2.1.1 Unstayed Polemast

The unstayed polemast is the simplest ship mast configuration. The main structure consists of a cantilevered tapered beam as shown in Figure 3.1. The beam generally has a hollow circular cross sectional shape, although other shapes such as hollow rectangular shapes are also possible. A typical unstayed steel polemast considered by Liang et al. (1994) had the following dimensions: Length of mast = 19m; Diameter at base = 1.27m; Diameter at tip = 0.76; and Thickness = 7mm. This mast was optimally designed to support a 2700 kg of radar antenna equipment under various sea loading conditions. As shown in Figure 3.1, the unstayed polemast may have secondary structures for supporting the radar antenna and other equipment.

Unstayed polemasts can also be found on several US aircraft carriers such as the USS Kennedy shown in Figure 3.2 (a). Other known applications of unstayed polemast on US naval ships include the USS Oregon that was used in World War II and illustrated in Figure 3.2 (b). Unstayed polemasts are also used on Canadian survey and research ships such as the Quest and Endeavour, and on Canadian Coast Guard ships such as Pierre Radisson, Henry Larsen and Martha Black. Figure 3.3 illustrates some of the unstayed polemasts on Canadian Ships.

3.2.1.2 Stayed (or Guyed) Polemasts

Figure 3.4 shows the configuration of a typical stayed polemast. The main structure of the mast typically consists of a long beam having hollow circular cross-sections that is fixed to the ship deck. The beam is supported (or stayed) at several points by means of guys. Supporting the beam in this manner effectively reduces the unsupported length of the beam, thereby increasing the buckling strength of the mast. Additionally, the mast may have secondary structural components such as yard arms for supporting equipment and flags. Stayed polemasts are commonly used on sailboats and yachts. Stayed polemasts can also be found on some naval ships of Canada (Provider), UK, France and Japan (Sharpe, 1995). Figure 3.5 shows an application of a stayed polemast on a Canadian ship.

3.2.1.3 Three-Legged (Tripod) Mast

Figure 3.6 shows an illustration of a three-legged (or tripod) mast. It consists of a main trunk, having a circular or polygonal cross-section, and two struts, all of which are fixed to the supporting deck structure. The mast can have additional components such as yard arms for supporting equipment, as shown in the figure. The tripod mast can be seen on several Spruance class ships of the US fleet. For instance, Figure 3.7 shows the mast on the USS Stout (DDG 55) that was built at Ingall's Ship Building (Sharpe, 1995). However, tripod masts are generally not found on Canadian ships.

3.2.1.4 Four-Legged Lattice Masts

Figure 3.8 shows the configuration of a typical four-legged lattice mast. The main structure of the mast is of an open lattice construction that is fixed to the ship deck at four support points. The lattice configuration takes one of various shapes, such as those shown in Figure 3.9 (Ellis et al., 1998). The lattice members are typically made of hollow, or open cross-sections having various geometric shapes. Typical lattice cross-sections are shown in Figure 3.10.

The four-legged lattice mast is by far the most common mast configuration on Canadian naval ships, and indeed the navies of other advanced countries such as the US, Japan, Germany and France. Figures 3.11 and 3.12 show finite element models of the masts on Canada's HMCS Halifax and Iroquois. These figures illustrate the typical mast structures on Canadian ships. It is seen that, in addition to the main lattice structure, the mast has additional secondary support structures, which are also of lattice construction. These are used to support equipment.

Ellis et al. (1980, 1998) have performed several studies on metallic masts on Canadian warships. These studies were aimed at reducing the weight and the profile area of the masts. Some of the lattice configurations considered in their study are shown in Figure 3.9. Individual members of the lattice structure were considered to be slender ($l/r > 160$) and rigidly attached at their ends. Their study showed the importance of accounting for the effects of flexural, as well as axial deformations of the members. In addition, Ellis et al. (1998) have shown that the St. Andrew's

Cross (Figure 3.9(a)) and the Diamond (Figure 3.9(c)) configurations provided more strength than the other lattice configurations. Furthermore, they showed that by offsetting the diagonals in pre-stressed condition (Figure 3.9(b)) a 20% increase in the strength of the corresponding mast was possible (Ellis, 1980).

3.2.1.5 Enclosed Mast

There is little information on enclosed lattice masts. However, a steel enclosed mast is being evaluated by the Dutch Navy (Bosman, 2000). Figure 3.13 shows finite element models of the enclosed mast being evaluated. The mast consists of a stiffened shell structure having a polygonal cross-section, with varying dimensions along the height. The support structures consisting of stiffened plates with cutouts are attached inside the main structure, at several points along the height as shown in Figure 3.13(b). These structures are used to support radar and other electronic equipment that are completely enclosed in the mast.

3.2.2 Material Systems

The most common metals used to construct ship masts are steel and aluminum alloys. Typical materials that have been used for masts include (Norwood, 1977):

a. Steel: Tubular shapes in T1 or T1A
Plates (for gussets) CSA G40.21 grade 44T (yield strength of 303MPa (44 ksi)

b. Aluminum: Tubular shapes X7004 temper T1 eg. Alcan 745 temper T4A plates (for gussets) 5083 temper H311 eg. Alcan D545 temper H31A

The selection of materials for mast applications is based on the following major desired characteristics of materials:

a. Low density;
b. High strength and stiffness;
c. Ease of fabrication (weldability);
d. Resistance to temperature and native environment;
d. Resistance to brittle fracture; and
e. Low cost.

3.2.3 Design and Analysis of Mast Structures

The analysis and design of ship masts and similar structures (such as transmission towers) has received considerable attention over the years and design guides dating back to the 1950s have been developed by the US Department of Navy (Liang et al., 1994) and by the Canadian Department of National Defence (Norwood, 1977). Key considerations in the design of ship masts include the following:

- Masts must be designed to withstand wind forces and dynamic loads due to ship motion to ensure a stable condition of the mast and to secure a good performance of radar and other alignment sensitive equipment;
- The weight of the mast must be kept to a minimum while also increasing the energy absorption capacity of the structure;
- Masts must be designed with proper consideration given to column strength and yield strength of the materials, as well as the joints and connections; and
- Mast design must consider blast and underwater shock effects on naval ship structures.

The design procedure developed by Norwood, 1977, is generally used for the design of masts for Canadian ships. The procedure is based on the premise that computer programs are available to assist in the analysis of the structure. The design steps are summarized here for the sake of completeness. Figure 3.14 shows the steps involved in the design and analysis of masts. Summaries of the various steps are provided below.

Step 1: involves the preparation of a complete list of antenna and other equipment to be carried by the mast, including the weight and overall dimensions, mounting details, clearance requirements and sketches showing preferred arrangement of each item.

Step 2: involves the definition of the overall dimensions, including attached equipment locations, geometry and mass based on Step 1 information.

Step 3: involves the definition of loading conditions. Masts are designed to withstand a wide range of loads and load combinations. The loads include self weight, equipment loads, sea generated ship motion, weather generated winds, and, if applicable, air blast and underwater shock.

In *Step 4:* the failure and serviceability conditions are defined. These include the maximum permissible mast displacements, rotations, stresses, accelerations and resonant frequencies.

Step 5: involves the selection of a preliminary mast configuration based on steps 2 and 3 and experience.

Step 6: involves the selection of material, including a definition of the material properties (eg. Young's modulus, yield stress, etc.)

Step 7: involves the development of the finite element model of the preliminary mast configuration. Knowledge and experience in finite element modeling is required to develop adequate and appropriate finite element idealizations that will provide reasonable assessments of the response quantities sought, vis-à-vis the cost of performing the analysis (see Norwood, 1977 for details).

Step 8: involves the computation of the first few natural frequencies of the mast structure. These are compared with the rigid body motions (pitch and roll) of the ship and with the frequencies of any known significant forces, such as the propeller blade rate frequency. To avoid the occurrence of resonance, the fundamental frequencies of the mast must not be close to any of these frequencies. If this is the case, then the mast configuration has to be modified to increase its natural frequencies.

In *Step 9:* a decision has to be made on the type of loading (ie static or dynamic) to be considered. Although most of the loads acting on the mast are dynamic in nature, equivalent static analysis procedures can be adopted in some cases, without loss of

accuracy, while also reducing the computation effort and cost. Detailed description on the selection of the load type is provided by Norwood, (1977).

Step 10: involves the determining of the loads at each joint of the structure (see Norwood, 1977).

Step 11: involves the definition of structural damping for the mast if a dynamic analysis is to be performed. Although the effects of damping on the structures are small, it is generally recommended to include damping in the analysis. In the absence of exact values for damping, reasonable values for steel and aluminum are 0.5 and 3%, respectively (Norwood, 1977).

Step 12: involves the computation of displacements and stresses due to the various types of loads, including (a) sea generated ship motions; (b) weather generated winds, and if applicable (c) air blast; and (d) underwater shock.

Finally, *Step 13:* involves the assessment of the design by comparing the displacements and stresses from Step 12 and the failure and serviceability criteria defined in Step 4. If criteria are violated, then modifications have to be made to the mast configuration, and a re-analysis will be required. This process is repeated until a satisfactory design is achieved.

A software tool based on the above design procedure was developed by Martec Limited in 1977. This software tool has been used for several analysis and/or redesign of existing Canadian warship masts, including the Improved St. Laurent, the Mackenzie, the Improved Restigouche, the DDH 265, the HMCS Gatineau, the DDH 280, the Iroquois and the new patrol frigates (Norwood and DesRochers, 1985). Recently, Martec has developed a special application interface for warship mast analysis within the DSA (DSA-GP, 1999) system. This interface provides the user with an easy to use procedure for the analysis, evaluation and redesign of both new and existing masts. Within the DSA system, the user can graphically verify and update the mast model, specify and verify all types of mast loading, evaluate the structure adequately using special built-in assessment

algorithms, and conduct buckling, vibration and response spectrum analysis. The DSA system also provides two-way translation between other commercial FEA codes.

Other mast analysis/design software are discussed in the literature. Some of these include the G-MAST and MAINMAST programs developed by Thomcast of France and Ramboll of Denmark, respectively. G-MAST is a Windows-based program for the analysis and design of guyed masted structures used in electric power lines. It is a completely integrated nonlinear program with menu-based input and easy to interpret text or graphics summaries of the analysis and design results. The graphics module displays deflected shapes and shows the percent of capacity used for each component. For its analysis engine, G-MAST uses a simplified version of the general purpose program SAPS (Structural Analysis of Power and communication Systems). The mast is described by its uniform geometric and mechanical properties (cross section area, moment of inertia, allowable compression, allowable bending, etc.) The program is suited for rapid analysis and design of mast guyed mast structures (Thomcast (1999)).

MAINMAST is also a Windows-based computer program for the analysis and design of cantilever towers and guyed masts that are exposed to wind and ice load. It is based on the Finite Element Method and all kinds of loads and load combinations, guy arrangement etc. may be taken into account. It has capabilities for static, free vibration and dynamic analyses. The results from a MAINMAST analysis include: (RAMBOLL, 1999).

- Node displacements
- Sectional forces in the mast
- Reaction at the mast foundation
- Guy forces and guy reactions on mast and foundation
- Lattice forces
- Pipe stresses
- Summary of total load on masts and guy elements
- Eigen frequencies
- Modal masses
- Life times

3.2.4 Joining and Repair of Metallic Mast Structural Components

Components of metallic mast structures are generally joined and repaired by welding. Welded connections can be designed with or without gusset plates. Connections without gusset plates are more aesthetically pleasing and more aerodynamically efficient than those with gusset plates. However, Canadian naval ship design practices require the use of gusset plates (Norwood, 1977). These are very useful for tubular connections, especially three dimensional connections.

Modelling, analysis and design of joints of mast structures is a critical element in the design of masts. For latticed mast structures, the joints could be very complex and special skills and knowledge are required to model these effectively. Martec's Warship Mast Program offers a procedure for global/local analysis for more accurate assessment of latticed mast joints. An example of such a global/local analysis of a gusset-plated connection between a horizontal brace and two diagonal braces is shown in Figure 3.15. Figure 3.16 shows a more complex local model of a typical main leg to brace joint. Figure 3.17 (a) shows a simple tubular joint connection, which could be of either metal or composite material. All local models shown were generated using existing modeling capabilities in DSA. Displacements from the global analysis can be automatically extracted and applied to the local model as prescribed boundary conditions. Alternatively, global member end forces and moments can be automatically applied to the local model as shown in Figure 3.17 (b).

3.2.5 Application and Performance of Metallic Masts

All of the masts on Canadian naval ships and auxiliary vessels are made of metals (steel or aluminum), with most being of the lattice mast configuration. These masts have been in use for many years and provided good performance. However, research studies aimed at the reduction of the weight and profile area of these structures have been on-going for over two decades (Ellis et al, 1998). The interest in designing lightweight masts is still ongoing and has indeed been the main motivator for this study. Also, because the use of metals for mast structure may also limit the performance of radar and other electronic equipment, due to the possibility of electromagnetic interference caused by the presence of the metallic structure, there is growing interest in developing

masts with good stealth properties. It is expected these objectives can be achieved by the use of composite materials. Hence a review of composite masts is provided in the next section.

3.3 Composite Masts

The use of composite materials for ship mast structures offers significant advantages:

(i) Composite (eg. GRP) masts could achieve weights lower than steel and approximately the same as aluminum;

(ii) Better fire resistance could be obtained than that provided by aluminum.;

(iii) Composites can be used to enclose radar, providing protection for the sensitive equipment, as well as providing signature reduction and other operational benefits; and

(iv) The use of composites can lead to reduced maintenance and operational costs, and also facilitate future upgrades effectively.

Because of these advantages, many navies are interested in and have developed composite mast structures. Due to the classified and proprietary nature of these studies, and the fact that this particular application has not been fully developed, there is not much information in the literature on composite masts. However, some studies by allied navies (eg. USA and UK) have been reported in the open literature. Some of these are summarized below.

3.3.1 Composite Mast Configurations

3.3.1.1 Composite Polemasts (Stayed or Unstayed)

The configurations of composite polemasts (stayed or unstayed) are similar to their metallic counterparts (see Figures 3.1 and 3.4). The mast typically consists of a main structure, which is a vertical spar or beam that is fixed to the deck of the ship (or boat). The beam cross section is typically of a hollow circular shape. As with the metallic structures, the mast may contain secondary structural components such as yardarm that are used to support equipment.

Composite masts have been used on sailboats and yachts for about two decades. Carbon fiber reinforced plastics are generally used for these applications, due to the fact that carbon fibres have very high specific strengths and stiffness, resulting in a dramatic improvement in sailing performance (Quilty, 1998, Hassan, 1998). However, due to the high cost of carbon fibre, their use has been restricted to high performance racing yachts and cruising super yachts. A study was recently undertaken by Hassan, 1998 to design a pultruded GRP-CFRP hybrid composite mast for sailboat applications. The main motivation was to develop a cost effective mast design. Figure 3.18 shows the stayed polemast configuration considered in the study.

3.3.1.2 Tripod (Three-legged) Composite Masts

The configuration of the tripod composite mast is similar to the metal tripods, as illustrated in Figure 3.6. The mast consists of a main trunk, two struts, and yard arms for supporting equipment. The tripod composite masts that are found in the open literature are discussed below.

Critchfield et al, 1994 have reported the design, fabrication and prototype development of a tripod composite mast for naval ships. This was a demonstration study conducted under a Co-operative Research and Development Agreement (CRDA) between the US Naval Surface Center and Ingalls Shipbuilding. In this program, a one-half scale prototype mast that was 11 meters tall was developed and tested. Figure 3.19 shows an illustration of the mast. The main trunk, two

stays and yard arms, were fabricated with a hybrid E-glass and carbon in vinyl ester composite, using the Seamann Composites Injection Molding Process (SCRIMP). The main trunk was fabricated in two halves using the SCRIMP process and then assembled together using bolts and adhesive bonding. Figure 3.19 (b) illustrates the trunk details. The same fabrication process was used for the two stays and yard arms. Commercially available pultruded glass reinforced plastics (GRP) struts were used to support yard arms, and aluminum connection details were used at the extremities of the struts (Critchfield et al., 1994). The mast was designed to meet vibration, air blast and ballistic requirements. The use of composites provided a 20% weight reduction in comparison with an aluminum baseline design.

Another tripod composite mast that was investigated at the US Naval Research Laboratory was presented by Mast et al. 1995. The goals of their mast design were to achieve weight reduction as well as favourable radar characteristics. The DDG-51 class of frigates was selected as a candidate ship for the mast installation. The geometry is that of a tripod mast with a rectangular box beam and two struts with antenna platforms attached to it and the associated deckhouse. Figure 3.20 shows a finite element model of the tripod mast. The mast was approximately 17.2 m high, and had a 1.4 m square hollow section, with a thickness of 24.8 mm. The materials considered for the application included AS4/3501-6 and AS4/PEEK composites with +60/-60 layup configurations, with up to 130 plies. The study showed that AS4/3501-6 (thermoset) material had the capacity to absorb more energy than the AS4/PEEK (thermoplastic) material.

3.3.1.3 Composite Lattice Masts

Composite lattice structures have similar configurations as metal lattices. The applications of composite lattice masts found in the literature have focused mainly on aviation and space structures. Even though they have been known to be used for ship masts by the Defence Evaluation and Research Agency (DERA), UK, (Pegg, 2000), information on this application has not been found in the public domain. In the following brief, summaries of lattice composite structures for infrastructure and space application are provided.

Figure 3.21 shows a free standing lattice lower of rectangular cross section. This is a safety mast used for approach and sequential flash lights as part of airport ground lighting. The mast is manufactured from composite profiles using a modular construction concept that is patented. Special joints are used between segments for assembly on site. Heights of these masts range from 0.3 m to 25 m. The advantages of this mast include their lightweight and their immunity to electromagnetic fields (ALD, 1999).

A lattice composite mast for space applications has been presented by Midturi (1997). This was an all-fiber glass, large diameter super mast structure that was manufactured by Astro Aerospace Corporation in Carpinteria, California for NASA's Johnson Space Center in Houston. The mast structure was a 750 mm diameter three-longeron lattice boom structure. The diameter corresponded to the pitch circle passing through the centers of the three longerons. The lattice boom had a total length of 6.55 m, with 26 bays, each of which was 250 mm long. The boom was made of S-glass, except for the two large aluminum end plates. The diameter of the longerons was 11.43 mm; the battens (horizontal members) 7.87 mm; and the diagonal bars 3.81 mm. Efforts to get information on composite lattice structures on ships did not provide any. However, the above illustrations demonstrate the feasibility of latticed composite mast structures.

3.3.1.4 Enclosed Composite Masts

Enclosed composite masts have been investigated by the navies of advanced countries such as the UK and USA. The studies that have been reported in the open literature are highlighted below.

A technology demonstrator mast was developed by BAE Systems as a test structure to be installed in the UK Royal Navy's next class of destroyers, the Type 45. The mast is designed to form a key component of the ship's "upper superstructure". It comprises a steel substructure clad in advanced fibre reinforced plastic composite panels, which incorporate radar-absorbing layers. Sensors are installed in interchangeable modules mounted within the cladding. The philosophy of the mast is intended to support future surface warship designs and retrofit to existing ships (BAE, 2000). Figure 3.22 shows an artist's impression of the mast

The Defence Evaluation and Research Agency (DERA), UK, in conjunction with industrial partners have been investigating new stealth design concepts for a 2,500 ton vessel designated as the Sea Wraith. This vessel has several unique features, including two large enclosed composite mast structures as shown in Figure 3.23. The two masts were placed asymmetrically with respect to the fore-to-aft line, with the forward mast set to starboard and the aft one set to port (Harboe-Hansen 1997). The purpose of the asymmetric design was to create an ambiguous radar cross section (RCS) to confuse homing devices of attacking missiles. The sensors and radio equipment are completely enclosed in the radar reflective mast structures. As shown in the figure, the masts look like unstayed polemasts with very large rectangular cross-sections, tapering from the base to the top. Details of the internal structures are not available to this study. However, it is expected that the mast will contain internal sandwich or stiffened plate structures with cut-outs, for supporting radar and other equipment, similar to the internal structural configuration of the metallic mast structure discussed in Section 3.2.1.5.

Another enclosed composite mast structure that has been developed, is the US navy sponsored Advanced Enclosed Mast/Sensor (AEM/S) system that was installed on the *Spruance-Class* destroyer Arthur Radford for trials in 1997, (Benson et al, (1998)). The AEM/S mast was designed and constructed at the Carderock Division of the Naval Sea Warfare Center (NSWC) in

collaboration with industry experts. The AEM/S mast is a 28.4 m high hexagonal structure which is 10.7 m in diameter. It encloses existing radar and other sensitive equipment, protecting them from the environment thereby reducing maintenance requirements (Benson, 1998). Figure 3.24 shows the concept description of the mast. The lower half of the AEM/S system serves to hold up to the top half. The case of the lower half is balsa, with E-glass skins as illustrated in Figure 3.25. An electromagnetic (EM) shield compartment that used reflecting metallic shielding was included in a portion of the lower half of the mast test article to demonstrate the ability of the composite structure to meet EMI design requirements. The top half also contains a tailored sandwich composite material made up of a foam core, with frequency selective material, as well as GRP structural laminate skins. A finite element model of the complete mast is shown in Figure 3.26.

3.3.2 Composite Material Systems

Composite materials are designed materials. The properties and behaviour of a composite material depend on several factors, such as

- The fiber material (carbon, glass, Kevlar)
- The fiber form and configuration (roving, weave, chopped, lamination sequence)
- The resin material (thermoset, (eg. epoxy, vinyl esther); or thermoplastic, (eg. PEEK)).
- The fabrication method (hand lay-up, filament winding, injection moulding, pultrusion)
- Cure conditions (autoclave, room temperature cure, etc.

Thus, the same material can have dramatically different properties, depending on the above factors. It is therefore necessary that in describing composite materials for mast application, due consideration is given not only on materials, but also their form, configuration, as well as the fabrication and curing processes. In the following, brief descriptions of composite material systems that have been used for mast structures are highlighted:

- Carbon fiber reinforced composites are widely used for polemast structures for sailboats and yachts. Pre-pregs (unidirectional or weaves) are generally used with an epoxy resin, (Quilty, 1998) and the fibers can be laid up by filament winding or by hand lay-up.

- The development of a hybrid carbon – glass reinforced composite fabricated by the pultrusion process for yacht masts has been discussed by Hassan 1998.

- Glass reinforced plastics, fabricated by the SCRIMP process have been used for composite masts. (Critchfield et al. 1994), Benson et al 1998). Although S-Glass was the preferred choice for some of these applications, due to the superior impact properties of S-Glass, E-Glass was mostly used due to availability and costs. However, S-glass has been used for composite lattice structures for space applications (Midturi, 1997). Thermoset resins (such as vinyl/esther and epoxy) have generally been used for these applications.

- Commercially available pultruded glass reinforced plastic (GRP) composite materials have been used for composite mast applications (Critchfield et al, 1994).

- Carbon fiber reinforced composites with thermoset and thermoplastic resins (eg. AS4/3501-6 and AS4/PEEK) have been used for composite mast applications (Mast et al, 1995).

- Sandwich composites, with GRP laminate skins, and balsa or foam cores have been used by Benson et al, 1998 for the AEM/S enclosed composite mast.

- An unbalanced sandwich panel with titanium and GRP skins and a phenolic honey comb core was investigated for enclosed composite mast applications (Kwon et al, 1995). Titanium, with its high melting point, was considered as the inside skin because of concerns for fire. The GRP was made from plain weave glass in vinyl ester resin.

3.3.3 Design and Analysis of Composite Mast Structures

The development and application of composite masts are still in their infancy. Hence, design/analysis guides have not been well developed for composite masts. The general approach involves the use of existing guidelines for metallic mast structures in conjunction with extensive finite element modelling and physical testing of full scale or scaled prototypes. This approach has

been used by several composite mast investigators, such as Hassan 1998, Mast et al 1995, and Benson et al 1998. In the words of Benson et al, 1998, their approach was to *build a little, test a little*. It is conceivable that developers of the various composite mast programs may have their internal design/analysis guidelines, but these are not well documented in the open literature. Guidelines for the design of composites for marine structures have been developed by Green, 1997. This is an excellent resource that can be used in conjunction with guidelines such as that by Norwood 1977, to design composite masts.

3.3.4 Joining and Repair of Composite Mast Structures

Composite components of mast structures are joined by bolting or bonding, or a combination of both. The joints are designed to withstand various kinds of load such as compression, tension, fatigue and air blast. Figure 3.19 (b) shows a typical joining detail for the main trunk of the CRDA composite tripod mast (Critchfield, 1994). The joining of the two halves of the main trunk involved limited bolting and adhesive bonding. The AEM/S composite mast structure utilizes a bolted connection to the base and other structural components. As with the metallic mast structures, due attention should be given to adequately model the connections and composite mast. This can be achieved by detailed local modelling, as discussed in Section 3.2.4.

3.3.5 Fabrication and Installation of Composite Masts

Fabrication processes used for composite mast structures include:

- Hand lay-up;
- The use of commercially available pultruded parts;
- Pultrusion;
- Filament windings, and
- The SCRIMP (Seeman Composites Resin Infusion Molding Process).

The SCRIMP process is by far the most significant fabrication method that has been used for composite masts for naval ships. This is a vacuum resin transfer process that is less labour intensive and more efficient than the conventional hand lay-up process. It uses a single open-mold

and a patented resin distribution system for achieving aerospace quality composites; however, the method does not impose the usual stringent clean environments required for aerospace parts. The SCRIMP process produces composites with very high fiber contents (up to 70% by weight for glass) and very low void contents (less than 1%). The mechanical properties of composites produced by the SCRIMP process are comparable or greater than the properties of composites fabricated by conventional wet lay-up, or pre-preg and autoclave procedures (Critchfield, 1994; Benson, 1998).

The AEM/S enclosed mast has been installed on the USS Radford (Benson, 1998). An existing metallic lattice mast was replaced by the AEM/S system. The installation called for an ingenious support structure comprising of a welded aluminum structure. Due to the large size of the mast structure, ingenious solutions have to be devised for other difficult problems such as removal of the structure from their molds, and handling and transportation of the structure to the ship (Benson, 1998).

3.3.6 Application and Performance of Composite Masts

The AEM/S system represents the most significant composite mast structure reviewed in this study. As discussed in Section 3.3.5, this massive composite structure was installed on the USS Radford and commissioned in May 1997. Prior to the installation, the structural, combat, and electromagnetic interference systems were all tested, demonstrated and proven effective (Benson, 1998). One of the prime directives, in addition to the technical goals, was that the *mast shall not fall off the ship*. It is instructive, that in a recent accidental collision involving the USS Radford, in which the ship sustained substantial damage, the AEM/S system remained intact on the ship. Therefore, further demonstrating the good structural performance of the composite mast.

Carbon composite polemasts have been in use on sailboats and yachts for about two decades. These structures have also performed their intended functions (lighter, stronger, and faster boats) well. Stronger and lighter lattice boom structures for space applications have also been made possible by the use of composite lattice structures (Midturi, 1997). With the successful

applications, it is expected that the use of composites for ship masts will increase within the present decade.

3.4 Discussion

A review of metallic and composite masts was presented in this chapter. As expected, most of the mast structures on ship structures are constructed of metals. However, there is a growing interest in the use of composites for mesh structures and some demonstration articles have been developed and tested. It can be reasonably expected that more applications of composites for mast structures will be developed in the future, because of the significant advantages, such as lightweight, high strength and stiffness, and good stealth properties.

Ship masts, (composite or metallic) can be classified into four main types, namely the unstayed or unstayed polemast; stayed polemast, tripod mast, lattice mast, and enclosed mast. The (unstayed polemast is a very simple structure that is found on Canadian auxiliary ship structure, on sail boats, and on some US carriers. The tripod mast is generally not found on Canadian ships, but is largely used on US ships. The lattice mast is by far the most widely used on Canadian and other Navy ships, enclosed masts of composite or metal construction are now being considered by several Navies, such as the Dutch, US and UK. One of the main attractions of the enclosed mast is that it can completely enclose the radar and other sensitive equipment, thereby protecting them from the harsh marine environment.

Various configurations of the different types of masts were presented in this review. From these configurations, it is possible to determine general trends in the features (eg. geometry of mast trunks, type and configuration of support structures, etc.) and components of the various types of mast. These are used to develop the mast structural configurations as discussed in Chapter 4.

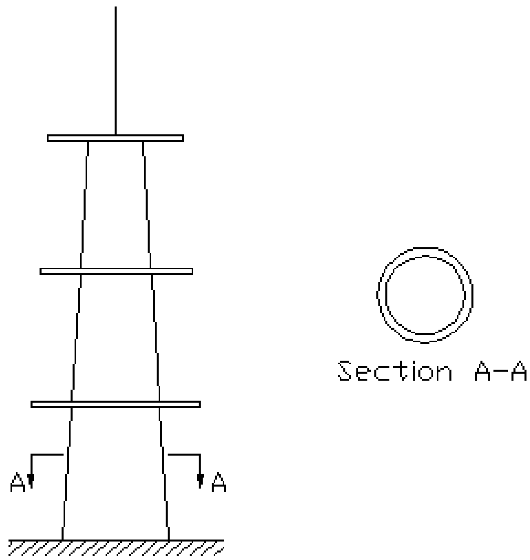


Figure 3.1: Unstayed Polemast

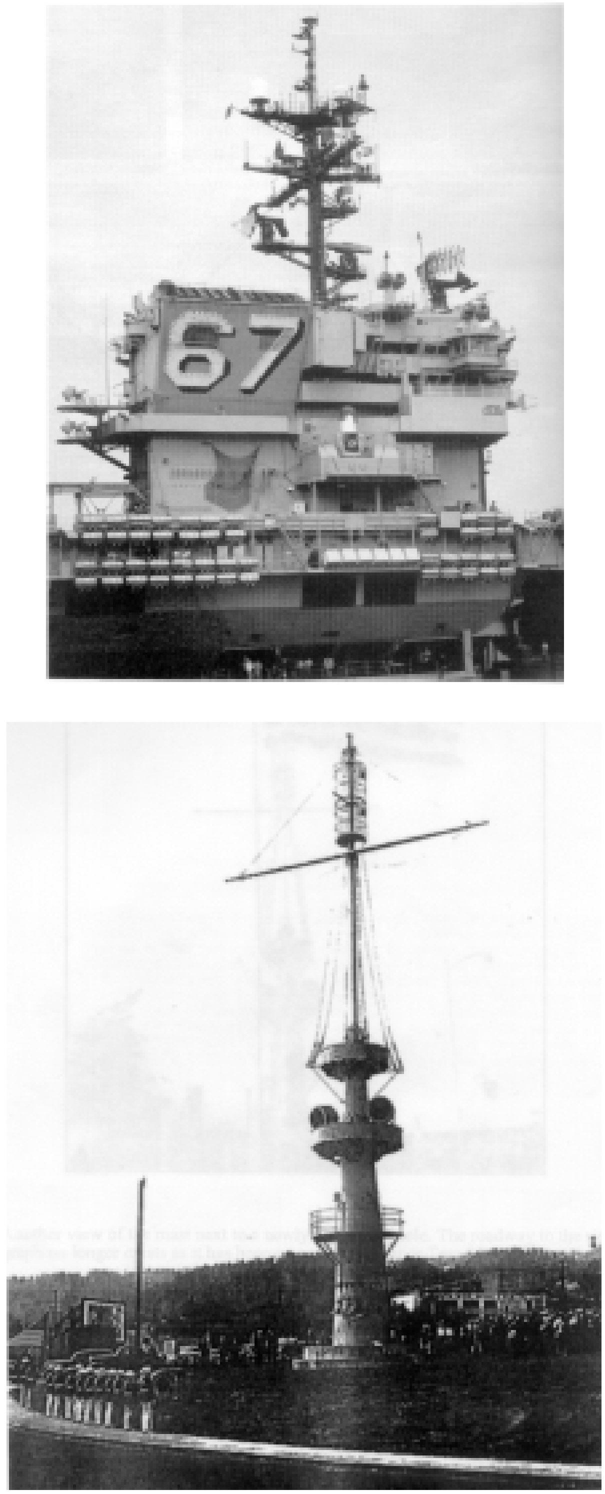


Figure 3.2: Application of Unstayed Polemast Structures on US ships
(a) USS Kennedy, (b) USS Oregon after WWII

PIERRE RADISSON 1/1993, van Ginderen Collection

SECHELT 1993, Canadian Maritime Command

Figure 3.3: Application of Unstayed Polemast Structures on Canadian Ships (a) Pierre Radisson, (b) Sechelt

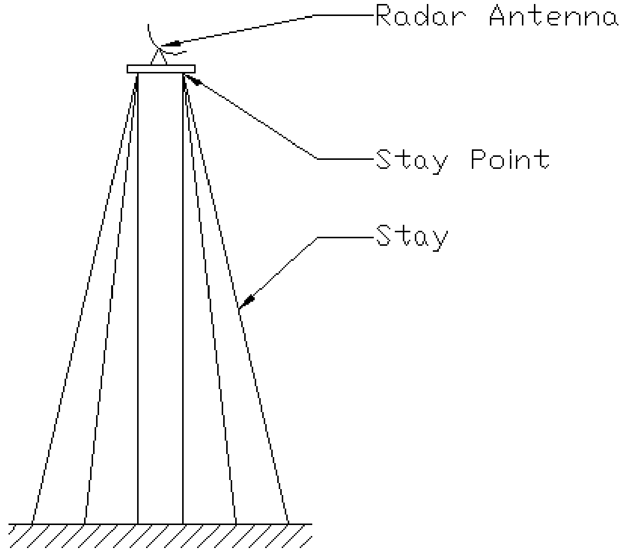


Figure 3.4: Configuration of a Stayed Polemast

Figure 3.5: Application of a Stayed Polemast Structure

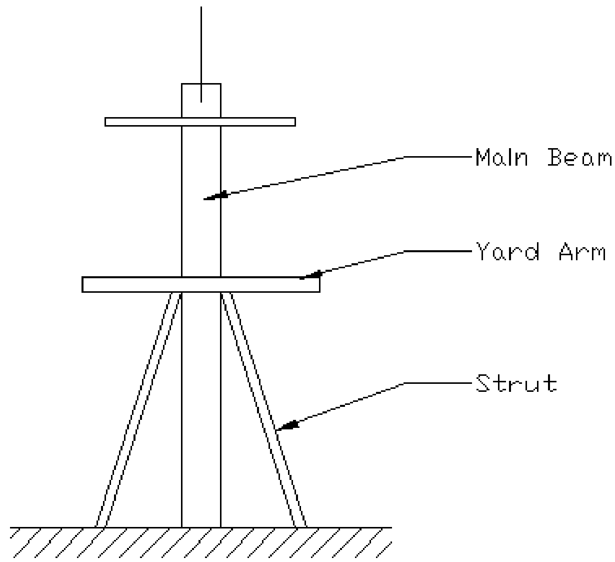


Figure 3.6: Illustration of a Tripod (Three-Legged) Mast

Figure 3.7: Application of a Tripod Mast Structure on USS Stout

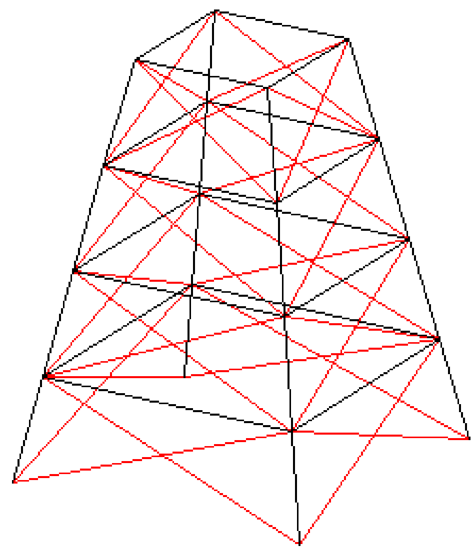


Figure 3.8: Configuration of Four-Legged Lattice Mast

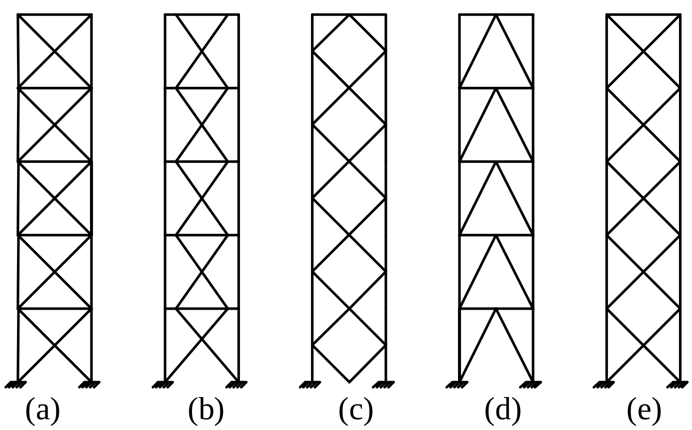


Figure 3.9: Lattice Mast Configurations (Ellis et al., 1998)

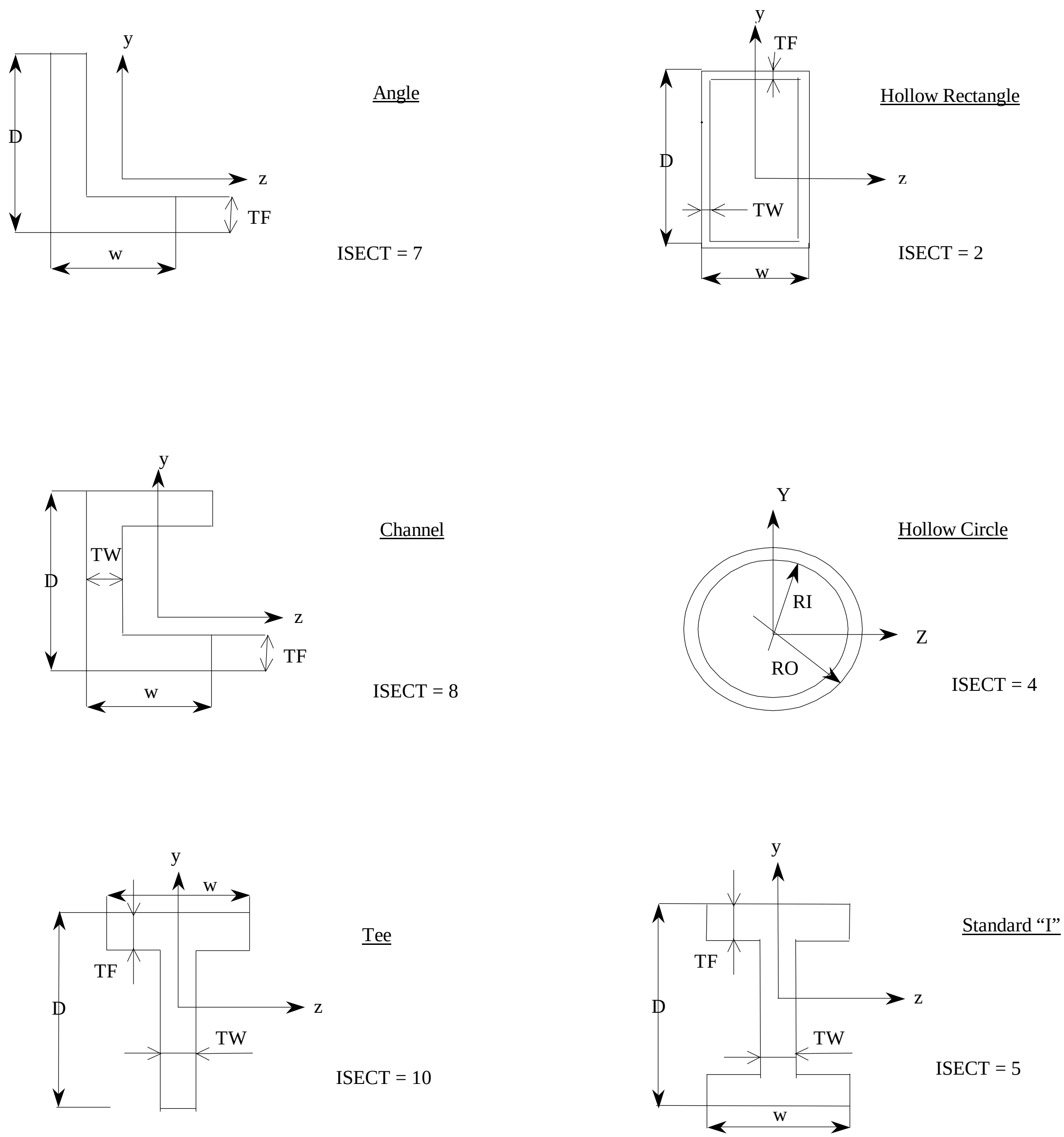


Figure 3.10: Typical Sections of Lattice Members

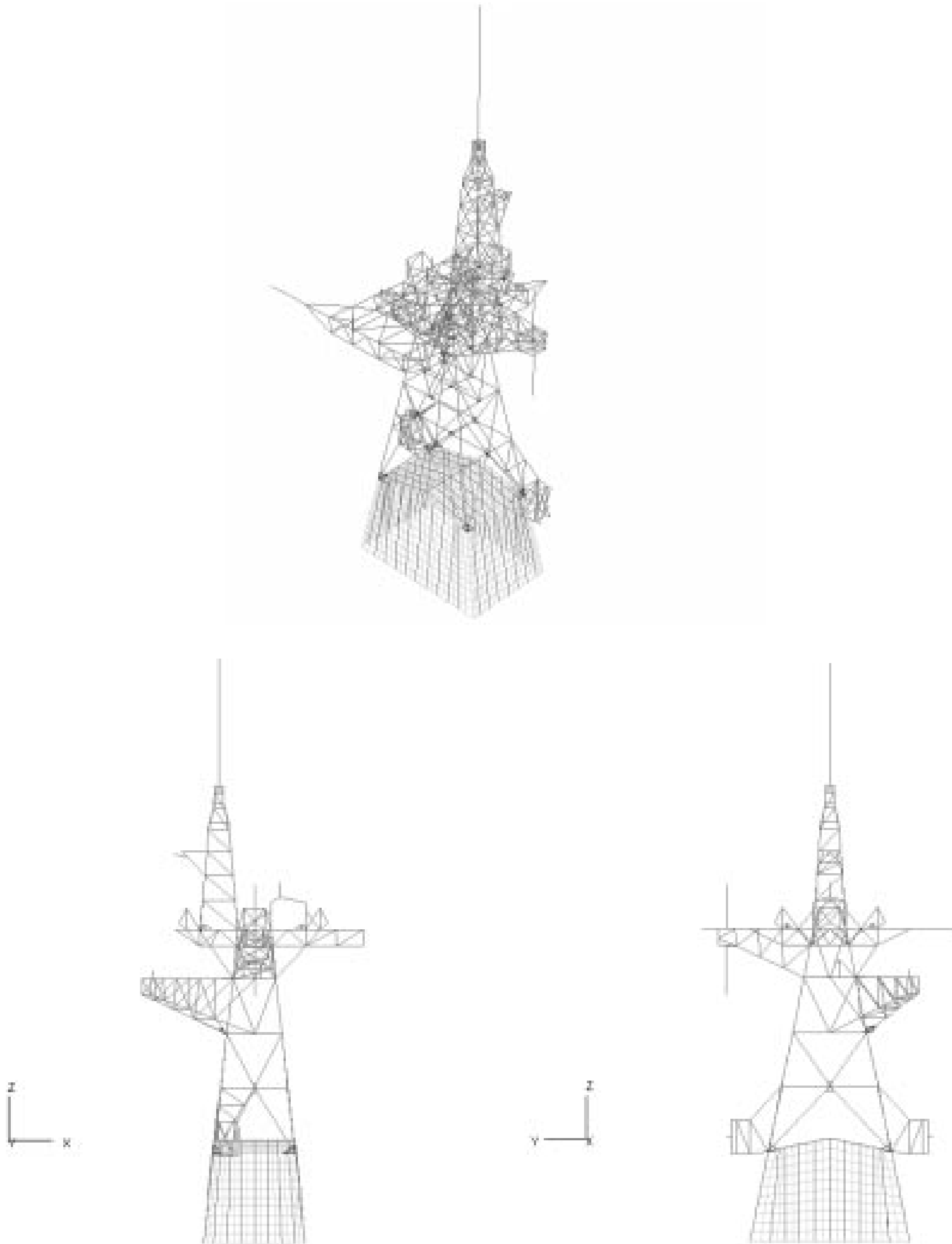


Figure 3.11: FE Model of Lattice Mast on HMCS Halifax

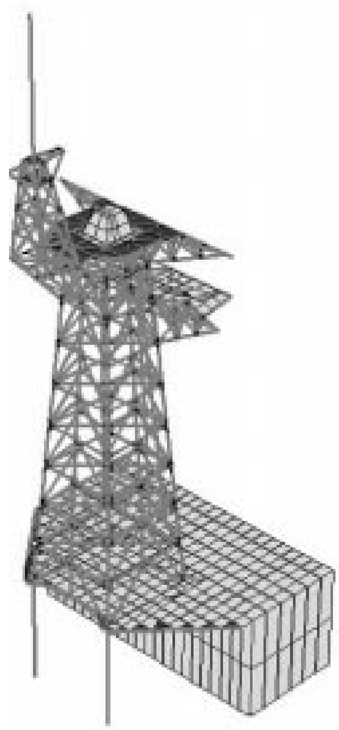


Figure 3.12: FE Model of Lattice Mast on HMCS Iroquois

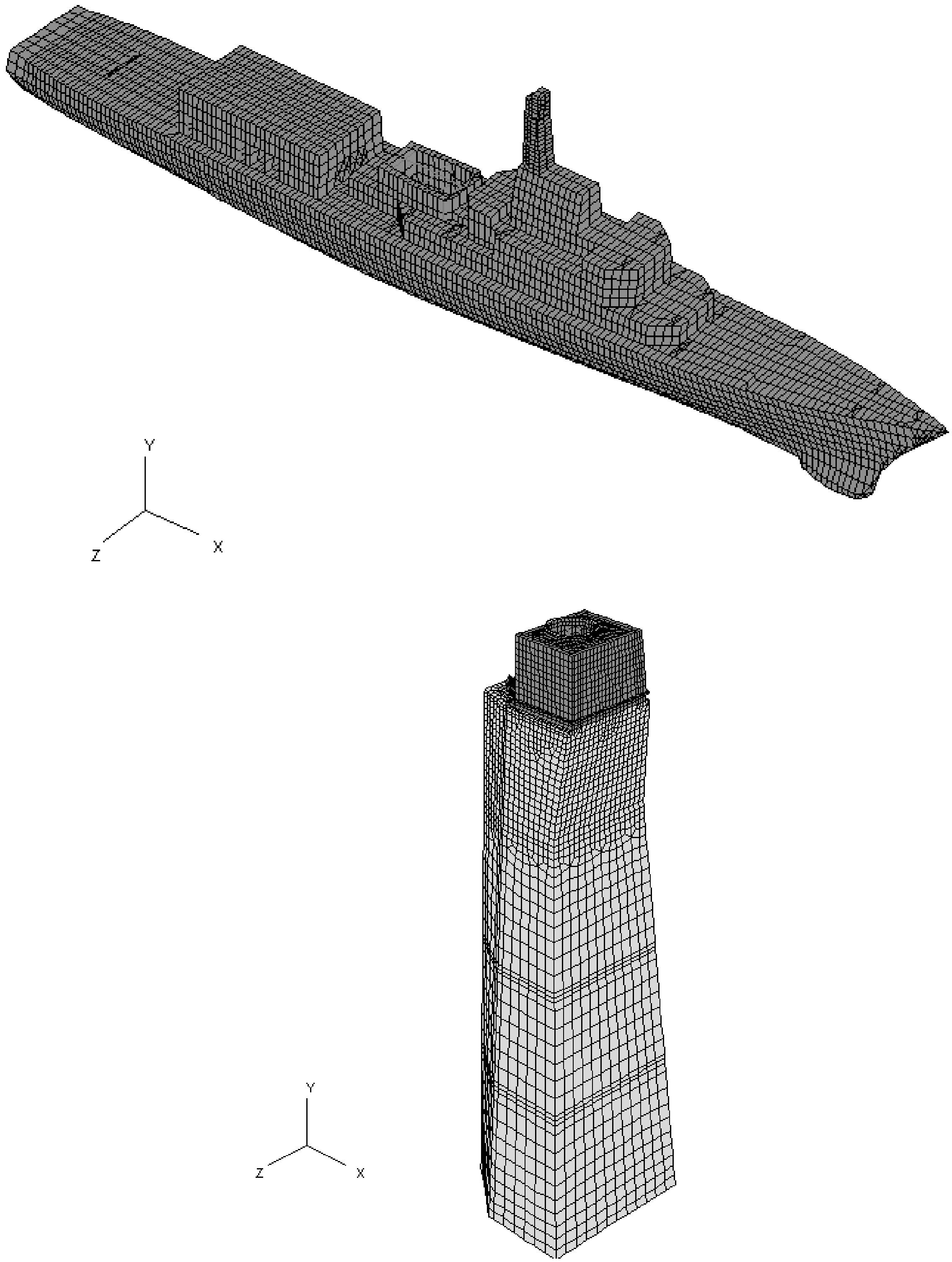


Figure 3.13: FE Models of Steel Enclosed Mast for Dutch Navy

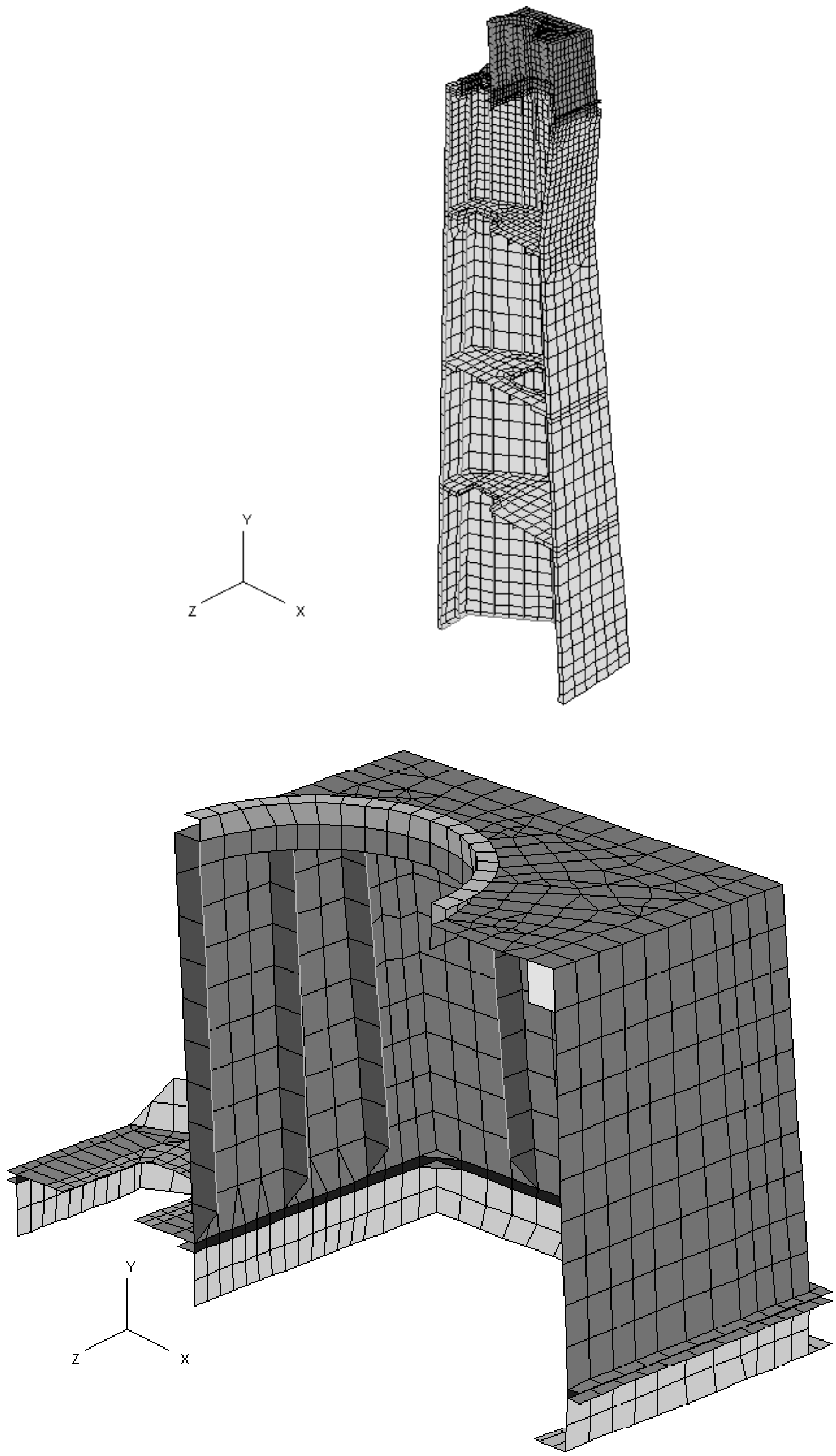


Figure 3-13 (continued): FE Models of Steel Enclosed Mast for Dutch Navy

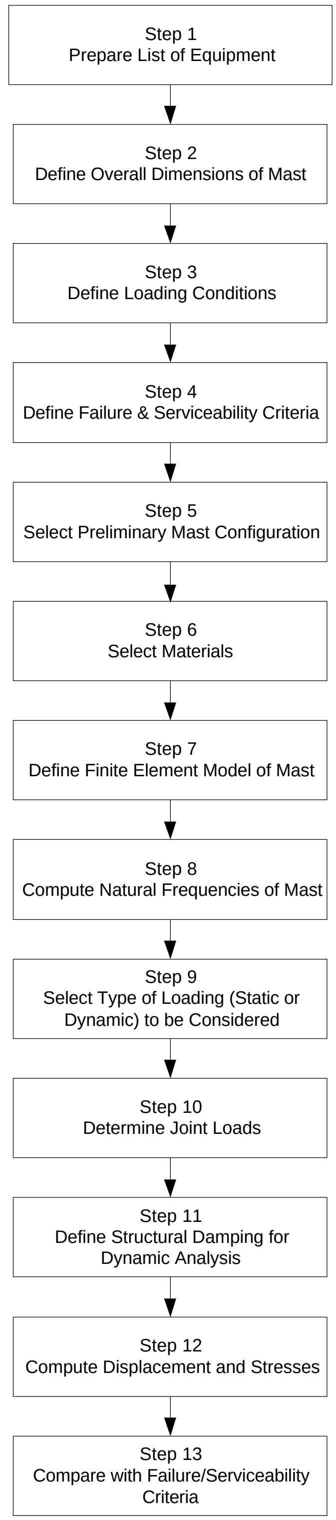


Figure 3.14: Steps for Design of Masts

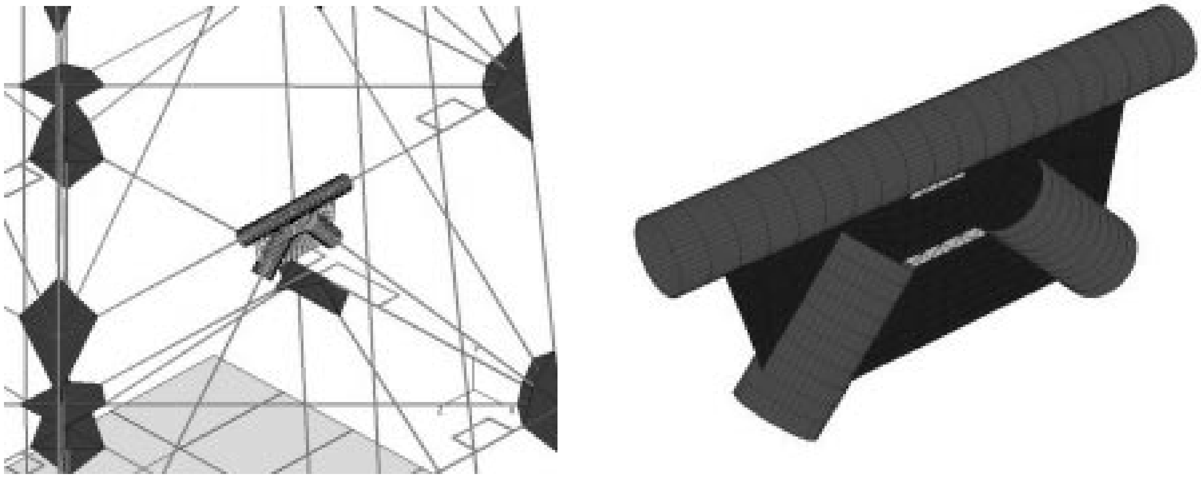


Figure 3.15: Gusset-Plated Connection with one Horizontal and Two Diagonal Braces

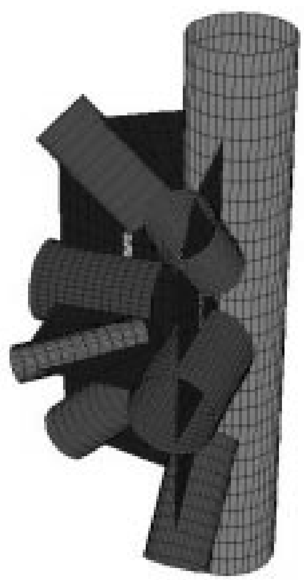


Figure 3.16: Model of a Complex Tubular Connection

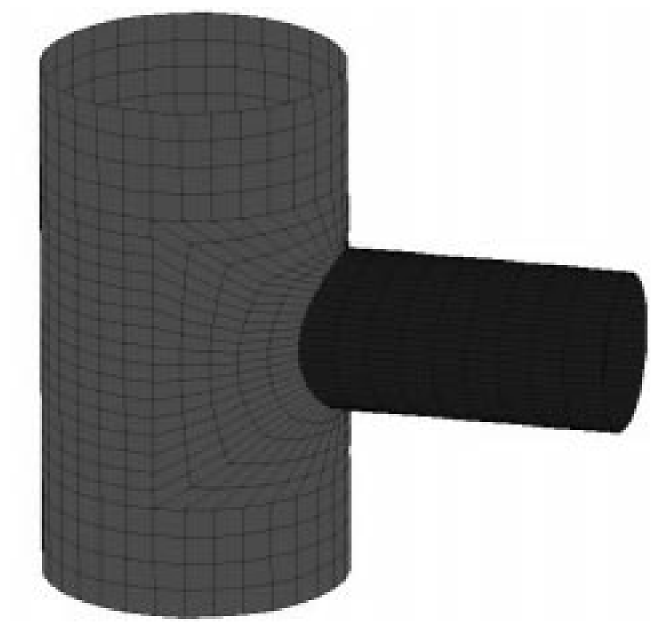


Figure 3.17 (a): Model of Simple Tubular Connection for Composite or Metal Joint

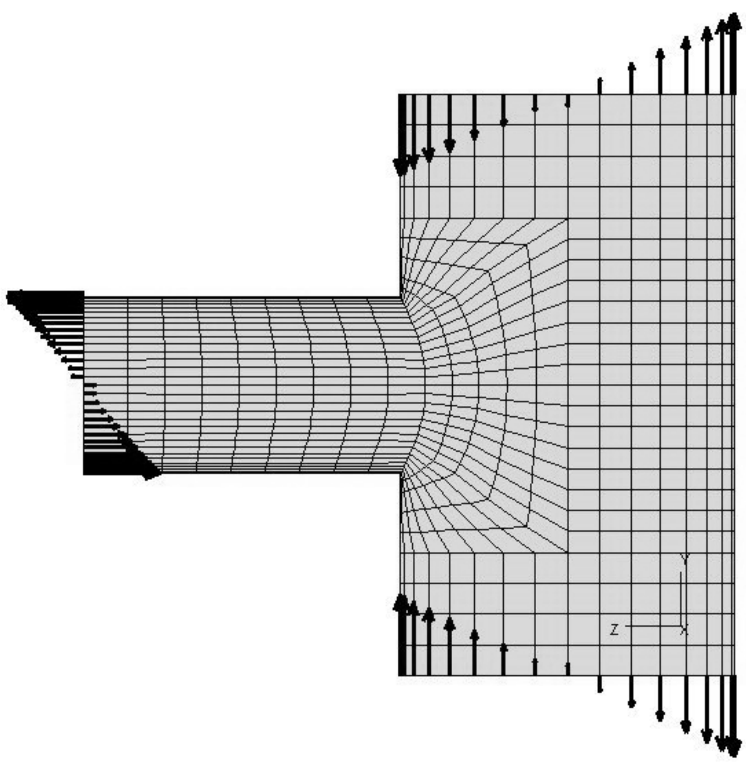


Figure 3.18 (b): Forces on Local Joint Model

Figure 3.19: Composite Polemast on Sail Boat (Hassan, 1998)

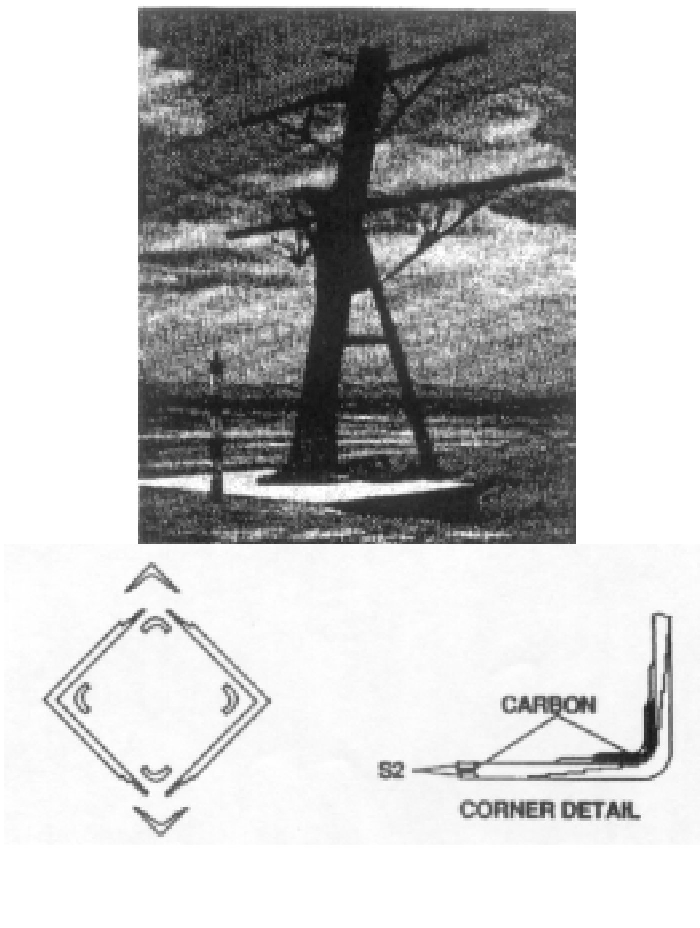


Figure 3.20: Illustration of CRDA Composite Tripod Mast:
(a) Half scale model; (b) Details of main trunk cross section (Critchfield et al, 1994)

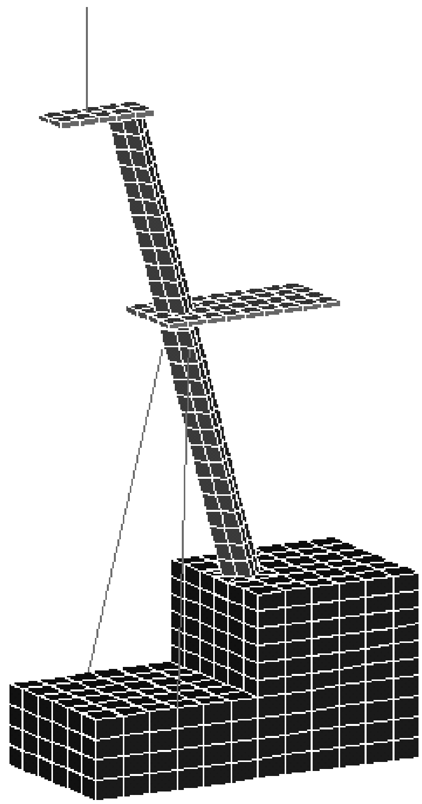


Figure 3.21: Finite Element Model of NRL Tripod Mast (Mast et al, 1995)

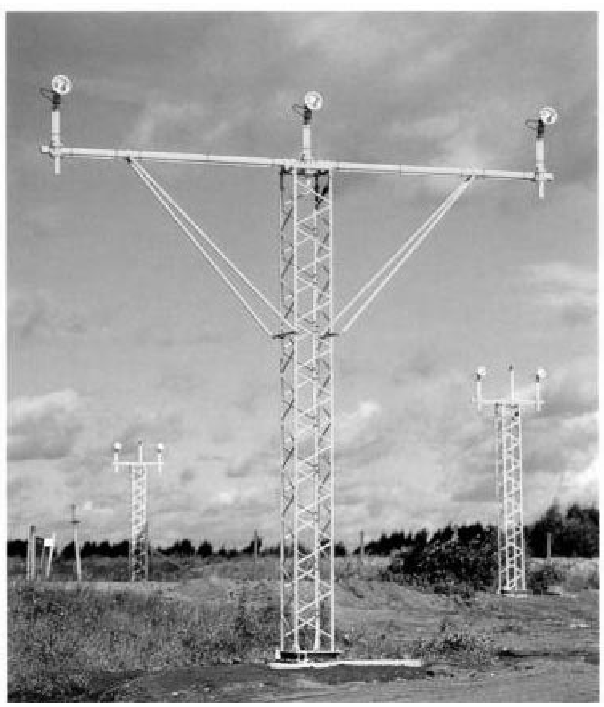


Figure 3.22: Composite Lattice mast for Airport Ground Lighting

Figure 3.23: Artist's Impression of UK Enclosed Composite Steel Mast

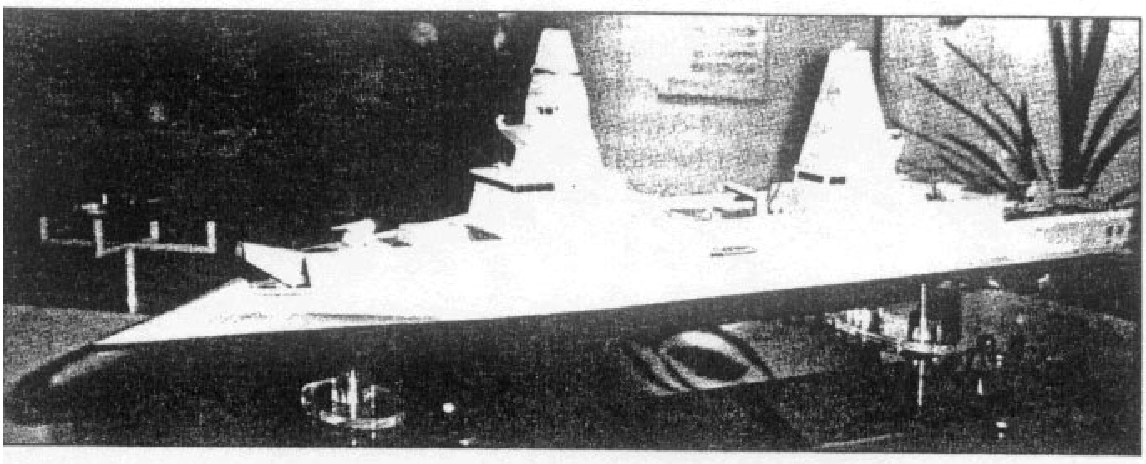


Figure 3.24: UK Composite Mast Structures (Harboe-Hansen 1997)

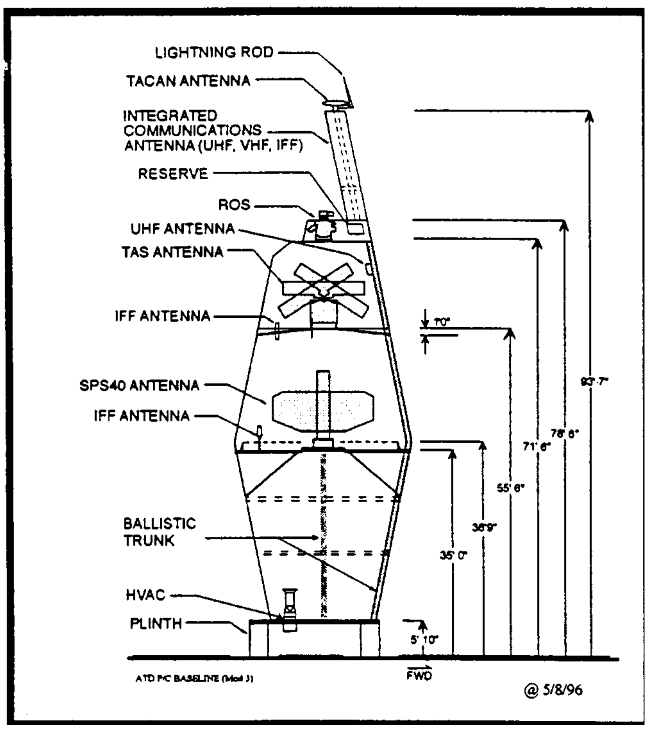


Figure 3.25: Concept of the AEM/S Enclosed Composite Mast

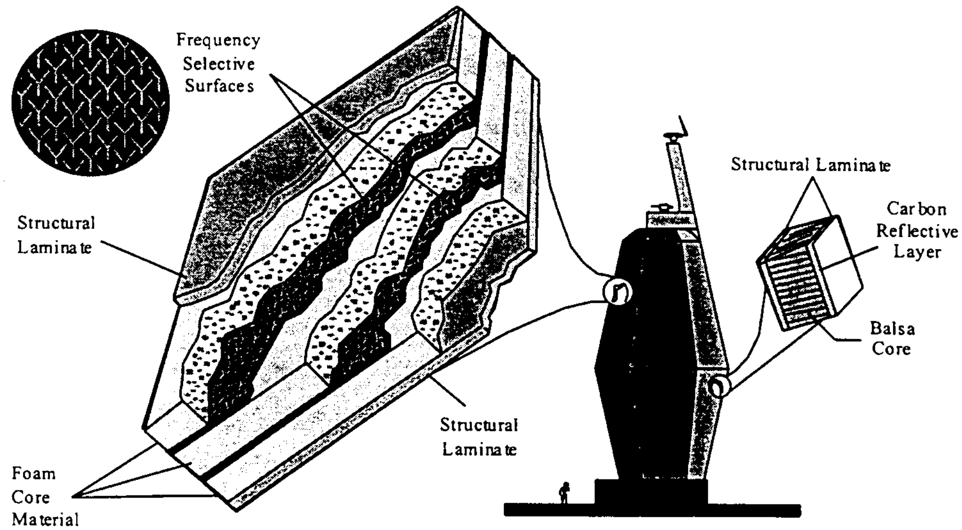


Figure 3.26: Tailored Composite Materials for the AEM/S Mast

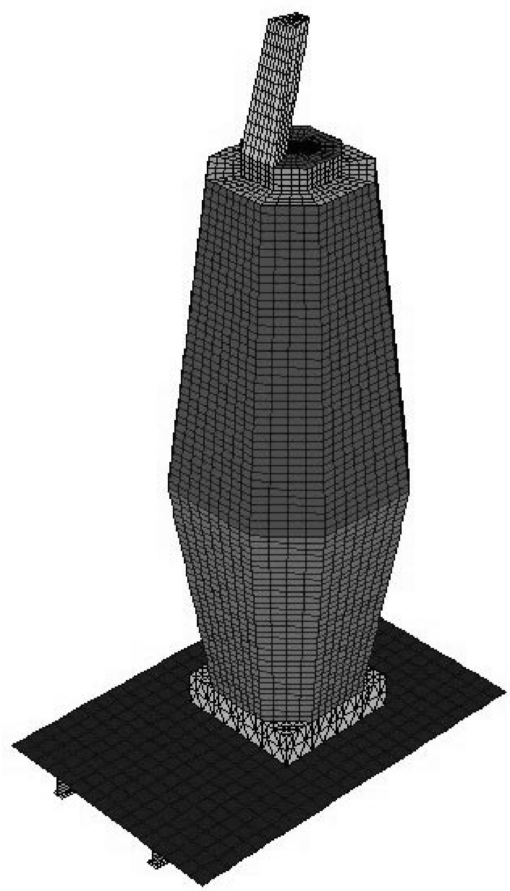


Figure 3.27: Finite Element Model of AEM/S Enclosed Composite Mast

4 COMPOSITE MAST SOFTWARE DESIGN AND PROTOTYPE DEVELOPMENT

4.1 Introduction

This chapter presents the requirements and design of the software system for rapid finite element modelling of masts. As stated in Chapter 1, the development of the mast modelling software is an initial step in fulfilling the requirement for a lightweight mast for the Halifax Class frigate, as part of mid-life refit. Following the review of finite element formulations for composites, and masts presented in Chapters 2 and 3, respectively, a list of requirements for the prototype software was prepared. This has been developed into a capability requirements document, which is presented in Section 4.2. The software system design was then addressed as presented in Section 4.3. An object oriented software development approach was selected to be consistent with modern software development practices. The development of a prototype software based on the design is presented in Chapter 5.

4.2 Capability Requirements

The main capability requirements of the MAST Analysis Software (MASTAS) system are illustrated in Figure 4.1. As shown in the figure, the software will have capabilities for:

- Geometry definition;
- Material property definition;
- Load definition;
- Boundary conditions definition;
- Finite element mesh generation;
- Display of the model;
- Analysis design set-up;
- Post-processing; and
- Interface with finite element and computer aided design (CAD) software.

Each of the main capabilities are discussed below.

4.2.1 Geometry Definition

The program shall have capabilities for defining the geometries of various mast configurations. The geometry is completely defined by the mast type, dimensions and orientation and equipment lists and their position. In addition, the program shall have the capability of graphically displaying the geometries as they are defined. Details of the requirements are provided below.

i. *Mast Type:* The mast types shall include polemasts (stayed or unstayed), tripods, lattice and enclosed masts.

ii. *Dimensions:* For each mast type set-up standard configuration shall be defined for the main trunk, stays, if any, yardarms, platforms and other support structures. For each configuration the program shall have the capability to set-up parameters for defining the geometry such as dimension/orientation and position with respect to a pre-defined reference frame.

Standard configurations for stayed or unstayed polemasts shall include:
- Main trunk (hollow circular or rectangular section);
- Stays (guys); and
- Yardarms (either unsupported plate or plate supported by truss system).

The parameters for defining the standard configuration for pole masts are shown in Table 4.1.

Standard configuration for tripod mast shall include:
- Main trunk (hollow circular or rectangular station);
- Stays (circular or rectangular rod, circular or rectangular tube); and
- Yardarms (unsupported or supported plate).

The parameters for defining the standard configuration for tripod masts are shown in Table 4.2.

Standard configurations for lattice masts shall include:
- Main trunk (one of possible lattice configurations, Figure 3.9);
- Auxiliary lattices (one of possible configurations, Figure 3.9); and
- Platforms/support structures (unsupported plate, or plate supported by truss structure). plate).

The parameters for defining the standard configuration for lattice masts are shown in Table 4.3.

Standard configurations for enclosed masts shall include:
- Main trunk (four-, five-, six- or n-sided);
- Internal platforms/support structure (stiffened structure, unstiffened structure with/without cut-outs, (solid composite or sandwich); and
- External platforms/support structure (stiffened structure, unstiffened structure (solid composite or sandwich)).

The parameters for defining the geometry of enclosed masts are presented in Table 4.4.

iii. *Equipment:* The program shall have capability to provide the masses of the equipment and their positions on various mast components.

iv. *Display of Geometry:* The program shall have capabilities for displaying the geometries as they are defined.

4.2.2 Material Definition

The program shall have capability to define material properties for the mast structural components. Types of materials shall include metals and composites, including sandwich composites. Furthermore, for composite materials, the program shall have the capability for graphically displaying the laminate sequences. Details of the parameters for defining the materials are provided below.

i. *Metals:* The following properties are required:

- Elastic properties $(E, \nu, E_{T,\,\rho})$; and
- Strength properties $(\sigma_{yield}, \sigma_{ult})$.

where E, E_T are the elastic (Young's) and plastic modulus, respectively, ν, the Poisson's ratio and ρ the mass density. $(\sigma_{yield}, \sigma_{ult})$ are the yield and ultimate strengths of the metal.

ii. *Composite Materials, Including Sandwiches:* The following properties are required:

- Elastic properties (E_{11}, E_{22}, E_{33}, G_{12}, G_{23}, G_{13}, $<_{12}$, $<_{23}$, $<_{13}$);
- Strength properties: X_T, X_C, Y_T, Y_C, Z_T, Z_C, R, S, T where (X_T, Y_T, Z_T) are the lamina normal tensile strengths in the (1,2,3) material principal directions, (R,S,T) are the shear strengths in the (2-3, 1-3, 1-2) planes, respectively. (X_C, Y_C, Z_C) are the compressive strengths in the (1,2,3) material principal directions.
- Strain Capacities: $X_{\varepsilon T}$, $X_{\varepsilon C}$, $Y_{\varepsilon T}$, $Y_{\varepsilon C}$, $Z_{\varepsilon T}$, $Z_{\varepsilon C}$, R_ε, S_ε, T_ε, where $(X_{\varepsilon T}, Y_{\varepsilon T}, Z_{\varepsilon T})$, are the lamina strain capacities in tension in the (1,2,3) material principal directions, $R_\varepsilon, S_\varepsilon, T_\varepsilon$ are the shear strain capabilities in the (2-3, 1-3, 1-2) planes, and $(X_{\varepsilon C}, Y_{\varepsilon C}, Z_{\varepsilon C})$ are the compressive strain capacities in the (1,2,3) material principal directions.
- Laminate Sequences: ply orientations and thicknesses.

It is desirable to have a library of commonly used materials as well as capability for user defined materials that can also be added to the materials library for future use. For composite

materials, due consideration should be given to the source and method of fabrication (eg. pultrusion, hand laying SCRIMP) of the composites as these can have significant effects on the properties of the materials.

4.2.3 Load Definition

The program shall have capabilities for defining and displaying the loads to which the mast may be subjected. Types of loads shall include:

- Self weight;
- Live loads (snow, repair personnel, etc.);
- Sea generated ship motion;
- Weather generated winds;
- Air blast; and
- Underwater shock.

The parameters for defining the various types of loads are provided below.

i. *Self Weight:*
  - This is computed automatically from the geometry and material properties.

ii. *Life Loads*
  - Snow loads (may be important for enclosed masts with large surface area); and
  - Maintenance related loads.

iii. *Sea Generated Ship Motion*
  - Significant sea states; and
  - Roll, pitch, heave.

iv. *Weather Generated Wind Load*
  - Wind speed;
  - Wind direction (aft, starboard, quarter starboard, etc.);
  - Drag coefficient; and
  - Vortex shedding, flutter.

v. *Air Blast*
  - Maximum overpressure;
  - Duration;
  - Stand-off distance; and
  - Temperature and pressure.

vi. *Underwater Shock*

- Shock spectra.

4.2.4 Boundary Conditions

The program shall have capability to define boundary conditions for the mast finite element model. In general, the boundary conditions will be generated automatically for each mast configuration (the bases of the masts being fixed automatically). However, the capability for user defined boundary conditions should also be provided to account for other possible boundary conditions, such as when a deck structure encloses part of the mast.

4.2.5 Finite Element Mesh Generation

The program shall have capability for defining finite element meshes from the mast geometries defined in Section 4.2.1. The process of mesh generation shall be made automatic, as much as possible, with minimal user input in the selection of mesh parameters. However, options for manual mesh generation shall also be provided to enable the performance of such function as joining or refining elements. The detailed requirements are listed below.

i. *Parameters for Generating FE Mesh:* These include the mesh size/density, and selection of elements. Suitable element types shall include four- and eight-node quadrilateral shells, two- and three-node beams, eight- and 20-node solids, and three- and six-node triangular shells.

ii. *Mesh generation:* shall be automatic, with a manual generation as an option.

iii. *Mesh Integrity Checks:* These should include checks/inquiries on the element integrity (eg. compatibility of elements, element normals) using graphical or keyboard means.

iv. *Mesh Displays:* Capabilities should be available for providing hidden line and wire mesh plots of the finite element meshes.

4.2.6 Display Capabilities

The program should have the following display capabilities:

- Geometric entities;
- Finite element mesh;
- Boundary conditions;

- Loads;
- Composite laminate sequences;
- Element thickness contours;
- Zooming, rotating, panning, viewing; and
- Element shrinking.

4.2.7 Analysis/Design Set-up

The program shall have capabilities for defining the analysis and design set-up for a mast structure. It is understood that the analysis/design can be performed either within the MASTAS system or in any other user selection software system., such as MGDSA-VAST, ANSYS, ABAQUS, or NISA. Thus the program shall be capable of generating the input data for these software systems. Detailed descriptions of the analysis/design set-up data are provided below.

i. *Analysis Types:* The analysis types shall include:
- Static (linear or nonlinear);
- Natural frequency;
- Buckling; and
- Transient dynamic (linear or nonlinear).

ii. Analysis Parameters
- Static; For nonlinear analysis, set-up iteration method, convergence criteria; and
- Natural frequency: These shall include modes to be calculated, solution methods, convergence criteria.
- Buckling: These shall include modes to be calculated, solution methods, convergence criteria
- Transient dynamic: Time step

iii. Design Parameters
- Design variables
  Moduli: E_{11}, E_{22}, E_{33}, G_{12}, G_{23}, G13, $<_{12}$, $<_{23}$, $<_{13}$
  Strengths: FX_T, FX_C, FY_T, FY_C, FZ_T, FZ_C, FX_Y, FY_Z, FX_Z
- Objectives
  Fundamental frequencies, frequency separation
  Displacements
  Stresses
  Energy
- Optimization/design methods
  Sequential linear programming (SLP)
  Sequential quadratic programming (SQP)

4.2.8 Post-Processing

Post-processing capabilities are required to view the analysis/design results. However, it is understood, at this time, that such capabilities shall be provided outside of the MASTAS system. Thus post-processing of results shall be carried out in accordance with the selected analysis/design system (see Section 4.2.7).

4.2.9 Interface with FE/CAD Programs

The program shall have capabilities to provide interfaces with selected finite element and CAD programs. This interface shall largely involve the definition of analysis/design data for the selected external FE programs, (such as VAST, ANSYS, ABAQUS, NISA) as discussed in Section 4.2.7. However, backward interfaces might be required to import data from these programs into the MASTAS system. Additionally, it might be necessary to import mast geometries from programs such as AutoCAD and ProEngineer.

4.3 Software System Design

4.3.1 General System Requirement

In this task, the overall MASTAS software system requirements and system architecture were analyzed and defined. Consideration was given to several factors such as the client's (DREA's) requirements, modern software development strategies, programming languages, graphics tools and experience of the project team in software development and mast modelling.

Based on the review of the available tools against the above considerations, the following tools and technologies have been adopted for the software development of the mast system:

i. The software development shall be based on the Object Oriented Programming (OOP) technology, in keeping with modern software development practices and to meet DREA's requirements;
ii. C++ shall be the system's programming language, and Microsoft Visual Studio shall be the system development environment;

iii. OpenGL graphics system shall be used for graphical representations and manipulations,

based on the superior capabilities and features of Open GL;

iv. Microsoft Foundation Classes (MFC) shall be used for the Graphical User Interface (GUI) development; and

v. HOOD TK (Hierarchical Object Oriented Data Toolkit) system developed at DREA (Lichodzijewski and MacAdam, 1999) is adopted for the development of the MASTAS application.

The MASTAS system will be built based on the HOOD hierarchical structure and will take full advantage of the HOOD application framework. All MASTAS objects will inherit from HOOD base classes and thus they inherit all the functionality of the base classes such as searching, I/O, setting privileges, as well as graphics functionality such as drawing and picking.

Communications with other programs such as commercial FEA codes (VAST, NASTRAN, etc), mast load analysis programs developed at DREA and Martec, as well as other application programs such as DSA, must be taken into consideration in the development of the MASTAS software system.

4.3.2 System Architecture

The MASTAS system will be built upon the HOOD hierarchical structure. It will take full advantage of the HOOD system in model generation/modification, meshing, smart modeling, loading, executing analysis, etc. The capability requirements described in Section 4.2 will be realized, and the HOOD program organizations and data structures will be used for the MASTAS system development.

The MASTAS system will have a style consistent with other HOOD applications in terms of the menu settings and the graphical representations of the objects. However, the MASTAS system will have its own window resources in order to allow the user to conduct specialized tasks in a traditional Windows application style.

4.3.3 Development Procedures

For developing professional applications such as MASTAS, the following procedures need to be carried out.

Software Feasibility Study

The software feasibility study starts with analysis of current software and hardware technology: whether the defined system will be cost effective from a business point of view and whether the budget allocated is sufficient.

Requirement Definition and Requirement Specification

Requirement definition includes discussion with potential users as well as task analysis. It describes the software system from the end-user's point of view. The requirement specification will describe the system in more detail. It should be set out as a contract between the system procurer and the software developer. Sometimes the requirement definition and requirement specification is combined into the requirement document. The requirement document will be modified as the project carries on.

Software System Design

This task involves developing the design document for all significant aspects of the system's operation as described in the previous subtasks. The design process will utilize a CASE tool such as Rational Rose, and a class diagram of the design will be generated using the Unified Modeling Language (UML). The design document will provide both visual presentation of the program's operations, as well as textual descriptions of the objects, methods and data structures that will be used to achieve the proposed operations

Components Coding and Testing

This stage is the main body of software development. Generally, a large system is divided into different components. The interface between each component should be clearly defined. Each component is coded, documented, and tested by the programmer. During the software

development, it is likely that some errors will be discovered between the existing product and the requirement document and must be modified.

Component Integration and System Testing

At this stage, components are put together and testing of the whole system is carried out.

Acceptance Testing

This final stage involves the tests of the developed system by the client users. Test scenarios and examples will be carried out by the users and any errors or deficiencies will be reported to the system developers for further corrections/improvements.

Table 4.1: Parameters for Defining Geometry of Stayed or Unstayed Polemasts

Standard Configuration	Parameters
Main trunk	Number of modules defining main trunk. For each module • diameter, at top, (or length x width at top) • diameter at bottom (or length x width at bottom) • thickness at top • length/height of module • thickness at bottom
Stay	Number of guys. For each guy • point of attachment to trunk • x,y,z co-ordinates of other end of guy
Yardarm	Number of yardarm. For each unsupported yardarm • length, width, thickness • orientation (eg. w.r.t. fore end of ship) For each supported yardarm • length, width, thickness • orientation • end points of support members • sizes of support members (selected from library)

Table 4.2: Parameters for Defining Geometry of Tripod Masts

Standard Configuration	Parameters
Main trunk	Number of modules defining main trunk. For each module • diameter, at top, (or length x width at top) • diameter at bottom (or width at bottom) • thickness at top • thickness at bottom • length/height of module • orientation with respect to vertical
Stay	Number of stays. For each stay • point of attachment to trunk • x,y,z co-ordinates of other end of stay
Yardarm	• unsupported plate • plate supported by truss system

Table 4.3: Parameters for Defining Geometry of Lattice Mast

Standard Configurations	Parameters
Main trunk	Number of modules defining main trunk • length x width of cross-section at bottom • length x width of cross-section at top • height of module • member sizes (from library) verticals diagonals horizontals
Auxiliary lattice structure	Number of auxiliary lattice structures. For each auxiliary lattice structure • number of modules defining the structure • length x width of cross-section at bottom • length x width of cross-section at top • height of module • member sizes (from library) • verticals • diagonals • horizontals • position, with respect to a reference • orientation
Platforms/support structures	Number of platforms. For each unsupported platform structure • length x width x thickness of platform • position • orientation For each lattice supported platform structure • length x width x thickness of platform • configuration of lattice support • position of platform • orientation

Table 4.4: Parameters for Defining Geometry of Enclosed Masts

Standard Configurations	Parameters
Main trunk	Number of modules defining main trunk. For each module • dimensions of cross-section at bottom • dimensions of cross-section at top • height of module orientation
Internal platform/ support structures	• location of structure (along the height) • thickness of structure • location, shape and size of cut-out, if any (predefined cut-out shapes) • configuration, type and sizes of stiffeners, if any (predefined stiffener configurations, type and sizes)
External platform/ support structures	• location of structure (along the height) • shape, and dimensions of structure (predefined shapes) • orientation of structure • configuration, type and sizes of stiffeners, if any (predefined stiffener configurations, type and sizes)

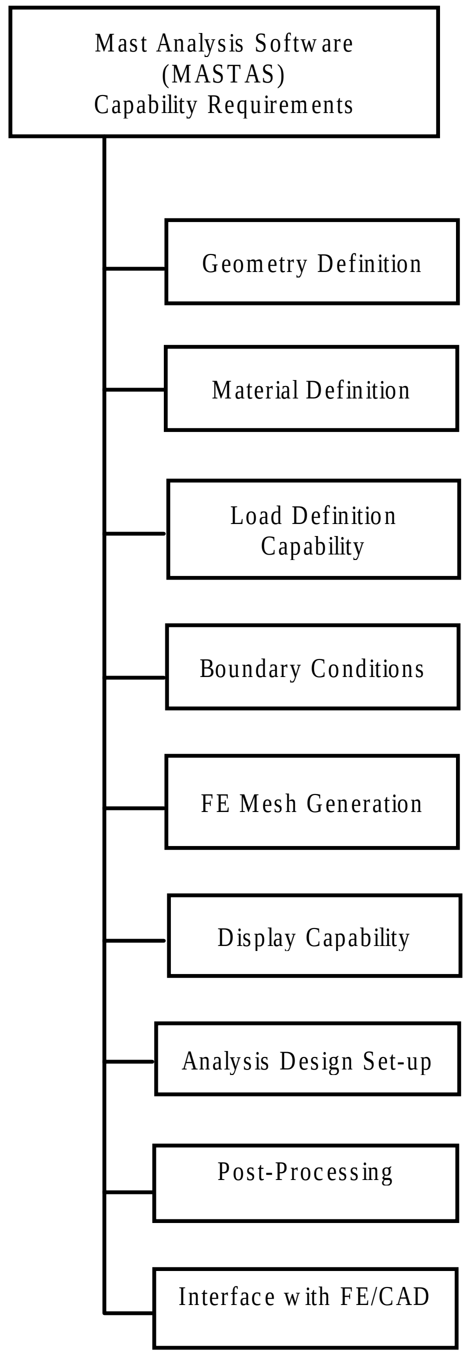


Figure 4.1: Capability Requirements of MAST Analysis Software (MASTAS) System

5. DEVELOPMENT OF PROTOTYPE MAST MODELING SOFTWARE

5.1 Introduction

The first task undertaken in the planning of the mast prototype application, an informal ranking of the available developments tools based on the following four criteria:

i. Compatibility with the object oriented design paradigm (OOP) (Horstann, 1997);
ii. Given the experience of the development team and DREA's requirements, C++ is the preferred programming language;
iii. Compatibility with the OpenGL graphics system (Open GL, 1997);
iv. Suitability for rapid development of applications involving graphics and simulation.

In addition to the four criteria outlined above, consideration was given to how the mast application would tie in with other software development efforts currently underway at Defense Research Establishment Atlantic (DREA). According to a recent report [Heath 2000], DREA has been investigating improved methods for software development and integration for the past five years. This effort has lead to the development of the HOOD TK (Hierarchical Object Oriented Data Toolkit) system, which incorporates object-oriented programming, code re-use, and VRML technology (Lichodzijewski and MacAdam, 1999).

Over the past several years the HOOD system has developed into a design methodology, providing software developers with a number of powerful features, including:

i. Encapsulation of graphics, database, GUI, event and window handling within a single framework;
ii. An object orientated toolkit for software development;
iii. Very strong implementation of re-use and object plug and play across applications.

The latter feature is an especially attractive feature of the HOOD system since it promotes the re-use of code written for other HOOD applications. In terms of the mast modelling and analysis tool this could prove to be extremely valuable due to the fact that HOOD applications already developed for finite element meshing or beam databases could easily be incorporated into the mast prototype. Given the criteria listed above, it was determined that the HOOD system was the most suitable candidate for implementing the mast prototype application. The decision to adopt HOOD

was also strengthen by the outcome of a number of similar software development projects (Heath 2000) where HOOD had proven to significantly reduce the time required to produce a working prototype. The success of these other projects greatly reduced the risk of cost overruns and/or delays in the development of the mast prototype.

5.2 Representing Mast Objects Within the HOOD Interface Hierarchy

In order to take full advantage of the HOOD application framework, it is necessary for all objects to inherit from one of the HOOD base classes (for a more complete treatment of HOOD please see reference Lichodzijewski and MacAdam, 1999). By doing so, the derived class automatically inherits all the functionality coded within the base. For the purposes of the mast prototype, the majority of the mast objects were derived directly from one of three HOOD classes: SFNode, SFGNode, or SFPNode (see Figure 5.1).

The first of these HOOD classes, SFNode, is the base class from which all HOOD objects are derived. It provides the mechanism by which an object can be stored in the HOOD hierarchy. The second HOOD base class, SFGNode, is itself derived from SFNode. In addition to the base functionality provided by SFNode, SFGNode includes additional graphics functionality (such as drawing and picking). As a result, all objects that require some form of graphical representation must be derived from the SFGNode class. The last of the principal HOOD classes used in the mast prototype, SFPNode, is derived from SFGNode. Besides the graphics capability inherited from SFGNode, SFPNode includes a data structure that provides all derived classes with the ability to own a collection of child objects. In addition, SFPNode's have pointers to the root SceneGraph (a tree structure listing all HOOD objects stored in the hierarchy- see Figure 5.2) and methods for accessing the child objects which it owns.

5.3 Mast Prototype Scope / Functionality

The prototyping exercise conducted for the purposes of this study provides a means for establishing and validating system requirements. As a result, prototyping is a technique that can often significantly reduce the risk associated with software development (Sommerville, 1992).

The prototype development strategy adopted for the mast application followed the four stages outlined by Sommerville (1992):

i. Establish the prototype objectives;
ii. Select functions for prototype inclusion;
iii. Develop the prototype;
iv. Evaluate the prototype.

In terms of the prototype objectives, the project team initially considered developing an interface through which the user would have the means to interact with both the application database and the analysis engines. Unfortunately this approach was later found to be too ambitious, and the prototype's scope was then limited to the development of the geometric modelling objects and their respective interfaces (i.e.: how the user interacts with the application in order to build a geometric representation of a mast).

5.4 Mast Prototype Objects

In order to satisfy the requirements set out for the geometric modeling of enclosed or lattices masts it was essential that the prototype provide the following capabilities:

i. Provide the means for representing masts by a collection of cross-sections;
ii. Allow for the coupling of structural components (yardarm, auxiliary masts, etc.);
iii. Generate lattice or enclosed bay structures.

In order to satisfy these requirements, four new class types (derived from HOOD base classes) were developed. Descriptions of each of these four classes are provided in detail in the sessions below.

5.4.1 Cross-sections

Cross-section objects represent the basic geometric building blocks for the mast application. The hierarchy for the cross-section class is provided below in Figure 5.3. Note that cross-sections are derived from the HOOD class SFGNode, and as a result, inherit the complete set

of HOOD graphics capabilities (i.e.: drawing, picking, etc.).

In the mast prototype application, mast cross-sections are defined by a series of coordinates, or points, represented in both local and global coordinates. The local representation is essentially a list of the two-dimensional in-plane coordinates of the cross-section (an additional attribute, named location, is used to represent the out-of-plane position of the section).

In addition to the base cross-section class, two derived cross-section objects were also developed for the mast prototype: *polygon cross-sections* and *generated polygon cross-sections*. For the most part, generated polygon cross-sections have very little additional functionality beyond what is coded in the base cross-section class. The main motivation behind the development of this object was to distinguish between different methods of defining a cross-section (i.e.: circular cross-sections could be defined by a center and radius as opposed to a collection of points).

Like *polygon cross-sections, generated polygon cross-sections* are also derived from the cross-section class. Unlike polygon cross-sections, however, the generated polygon cross-section class computes its coordinates by establishing references to two other cross-sections. Once these references have been established, generated cross-section objects use a weighted average of the points stored in these referenced cross-sections in order to compute its own cross-section coordinates. As a result, any changes made to either of the referenced cross-sections (i.e.: changes made to the height or location) will cause the generated polygon cross-section to re-calculate its own coordinates (see Figures 5.4a and 5.4b).

5.4.2 Multiple Cross-section Structures

Multiple cross-section structures (MCSS) are used to represent complex mast components (such as yardarms for example) whose geometry can be described using a series of cross-sections. In fact modelling MCSS objects as a series of cross-sections ultimately led to the decision to derive the MCSS class from the HOOD SFPNode class. By inheriting from the HOOD SFPNode, the MCSS class can “own” the cross-section objects used to define its geometry. In addition, since SFPNode is derived from the HOOD SFGNode, MCSS objects have full graphics functionality.

Early on in the development of the MCSS class, however, it became apparent that a single class could not efficiently handle the differences in behavior found in the various MCSS type objects. Specialization into a number of sub-classes appeared to be necessary, primarily to account for differences in how one type of MCSS formed relationships with another type of MCSS (i.e.: how a yardarm could attach itself to a trunk but how a trunk could not attach itself to a yardarm). As a result three new MCSS derived classes were developed: trunks, yardarms, and auxiliary masts.

Trunks are used to represent the main structural component of a mast (see Figure 5.5). Only one trunk object is permitted in any single mast model. Yardarms and auxiliary masts differ from the trunk class mainly in the way their attachments can be established. Both yardarms and auxiliary masts can form attachments to any other MCSS derived object (including trunks), but trunks cannot be attached to a yardarm or auxiliary mast.

5.4.3 Bay Generators

The construction of mast bays is the responsibility of the bay generator class. The attributes of this class (which is derived from the HOOD SFPNode class) include a series of three references: the first to a parent MCSS object, the second to an upper cross-section of the parent, and a third to a lower of cross-section of the parent. The upper and lower cross-sections are used to define the geometric boundaries of the bay (see Figure 5.6), and are also used for the graphical display of the bay object (note that because SFPNode is derived from SFGNode, bay generators are also graphics nodes).

In addition to the base class, two derived bay generator classes where also developed for the prototype application: lattice bay generators and enclosed bay generators. As suggested by their names, these two derived classes allow the user to create either lattice or enclosed masts. Upon construction, these bay generators create a series of lattice braces or panels (depending upon the bay type) which are stored as child nodes in the hierarchy (See Figure 5.6).

5.4.4 MCAttachment Objects

MCAttachment objects have been designed to perform the task of attaching (or coupling) two MCSS components. The attributes of this class include references to the two MCSS components to be joined: the parent MCSS and the target MCSS. In addition, the attachment class also includes references to the upper and lower cross-sections used to mark the location where the target MCSS will be attached to the parent MCSS.

In addition to the attributes mentioned above, MCAttachment objects inherit the complete set of HOOD graphics capabilities due to the fact that they are derived from the HOOD SFGNode class (see Figure 5.7).

5.5 Mast Object Interfaces

HOOD interfaces provide a means for the user to display and modify the attributes of an object residing in the scene graph hierarchy (see Figure 5.2). The interfaces themselves are a collection of property pages, with each individual page representing a particular level of inheritance in the object's hierarchy. The interface for the polygon cross-section class, for example, contains the property pages of each class in its inheritance chain: SFNode, SFGNode, CrossSection, and PolygonCrossSection (see Figure 5.8). Illustrations of the interfaces for the MCSS class and the bay generator class are also provided below in Figures 5.9 and 5.10 respectively.

5.6 Mast Wizard

In order to provide the user with a quick and relatively easy means of generating a mast model, a mast wizard was developed and implemented into the mast prototype code. Initially (see Figure 5.11) the wizard prompts the user for information regarding the mast type (lattice or enclosed), name, and number of components (yardarms, auxiliary masts, and platforms). Once this preliminary information has been supplied, the wizard then provides the user with a second form which is designed to allow for the geometric definition of each new mast component (see Figure 5.12).

In addition to the geometry description of mast component (see Figure 5.13), the wizard also provides users with the ability to define the nature of the component attachments (see Figure 5.14). Interfaces of the new created objects can also be viewed from within the wizard by selecting the view interface button (see Figure 5.15).

5.7 Demonstration

In the discussion to follow, an example of how a mast model can be generated using the prototype application is provided. For the purposes of this demonstration the mast model under consideration is relatively elementary: two yardarms connected to a trunk.

The first step in the procedure (see Figure 5.11) involves using the wizard to define the mast type (lattice) and the number of additional structural component (two yardarms). Next, the geometry of each major structural component (including the trunk) is defined. In this example the trunk has four legs and an overall length of 10 meters, and because it is made up of two bays, is defined by three structural cross-sections (or S-Sections as the are labeled in Figure 5.12). It should be noted that the wizard assumes a default cross-sectional area of one when generating the trunk and other structural components. However, if the user wishes to change these properties, the wizard can bring up the interface for the object in order to facilitate the necessary modifications (see Figure 5.15).

In terms of the two yardarms, each has an overall length of 6.0 m, and are attached to the upper bay of the trunk. The attachment process can be handled using the attachment facility implemented in the wizard. In the case of each yardarm, the mast trunk was selected as the valid attachment and the two cross-sections, representing the location on the trunk where the attachment is to be made, are highlighted in attachment box of the wizard form.

Once all the major structural components (MCSS objects) have been initially defined using the wizard, the user can modify the model using the object interfaces. For example, the middle cross-section of the trunk can be lowered by first picking this object graphically and then

modifying the location attribute found on the “CrossSection” page of its interface dialog (See Figures 5.16a and 5.16b). Other modifications could include changing the number of divisions in the lower trunk bay (see Figures 5.17a and 5.17b), or the size of the trunk base (see Figures 5.18a and 5.18b)

The example provided in the section above by no means reflects the full extent of the models that can be generated using the mast application. Figures 5.19 and 5.20 provide examples of far more complex mast structures that were created entirely using the mast prototype. In Figure 5.23 a lattice mast representative of the one installed on the CPF is provided. In Figure 5.24 a model of an enclosed mast is illustrated.

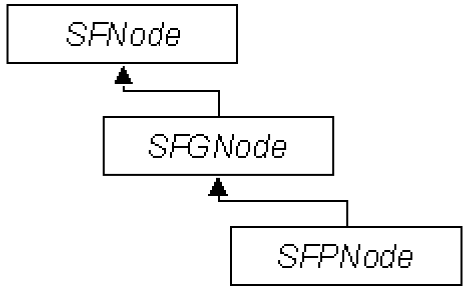


Figure 5.1: SFNode Class Hierarchy

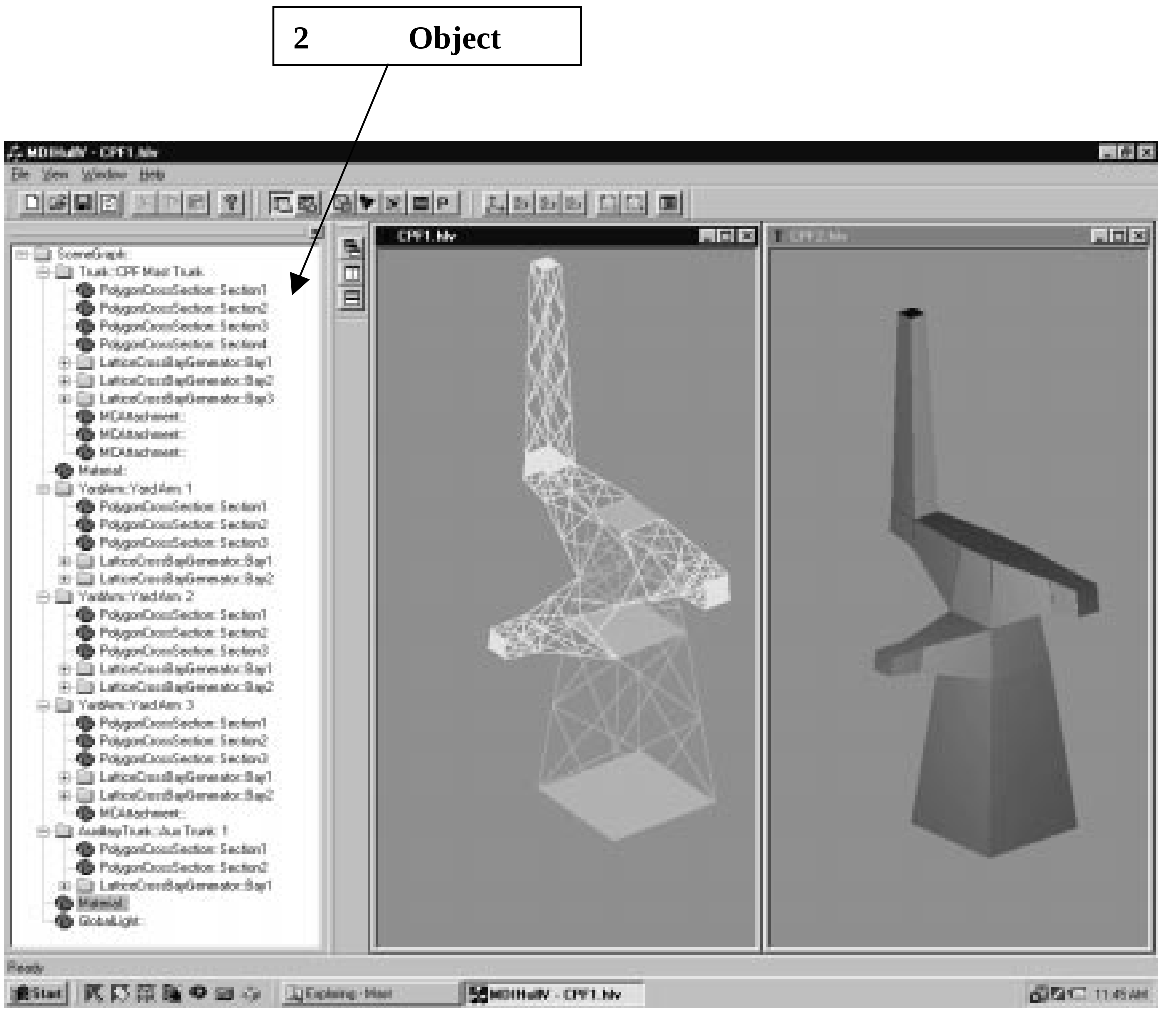


Figure 5.2: HOOD Scene Graph

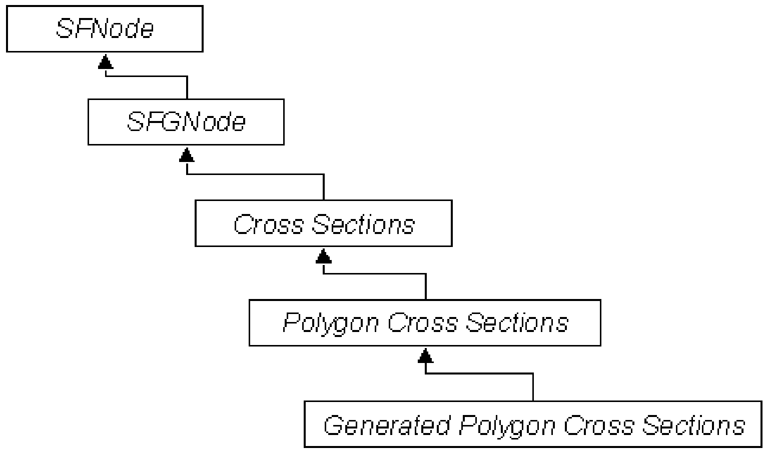


Figure 5.3: Cross-section Class Hierarchy

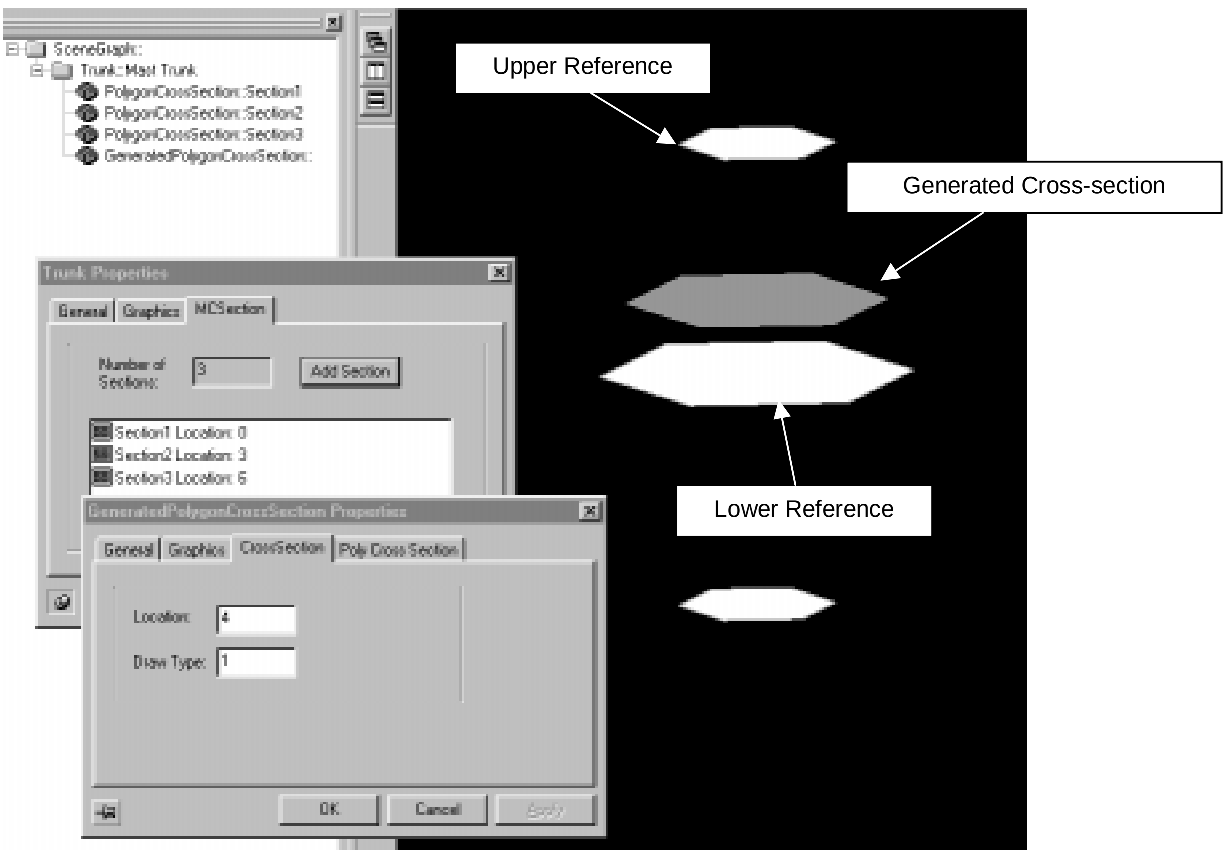


Figure 5.4a: Generated Polygon Cross-section (Before Modification to Reference Sections)

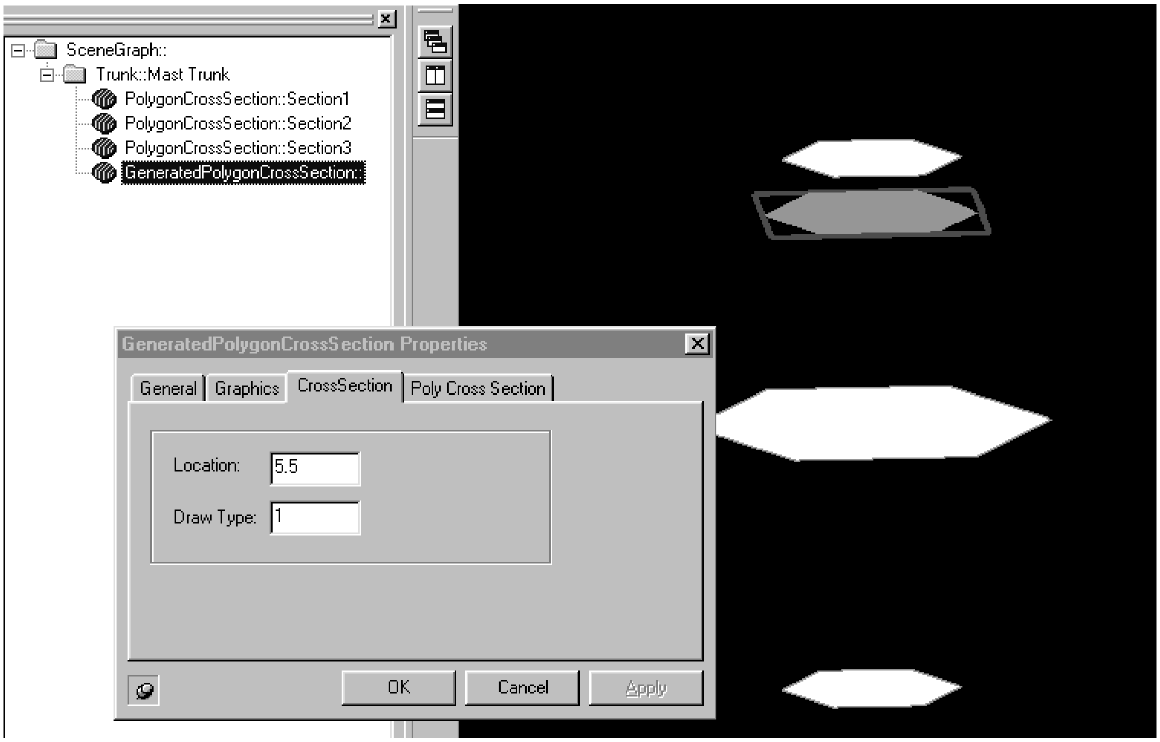


Figure 5.4b: Generated Polygon Cross-section (After Modification to Reference Sections)

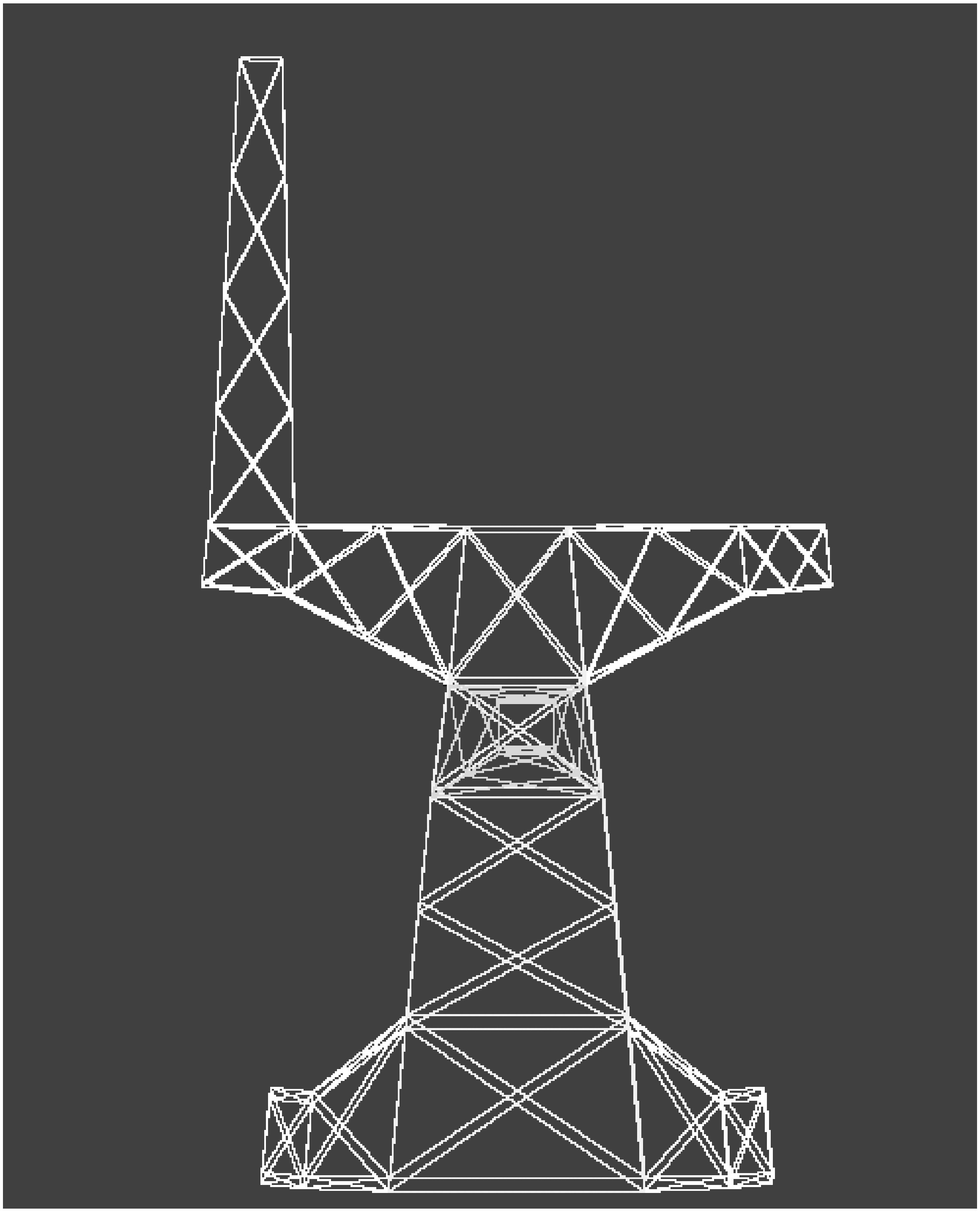


Figure 5.5: Trunk Mast

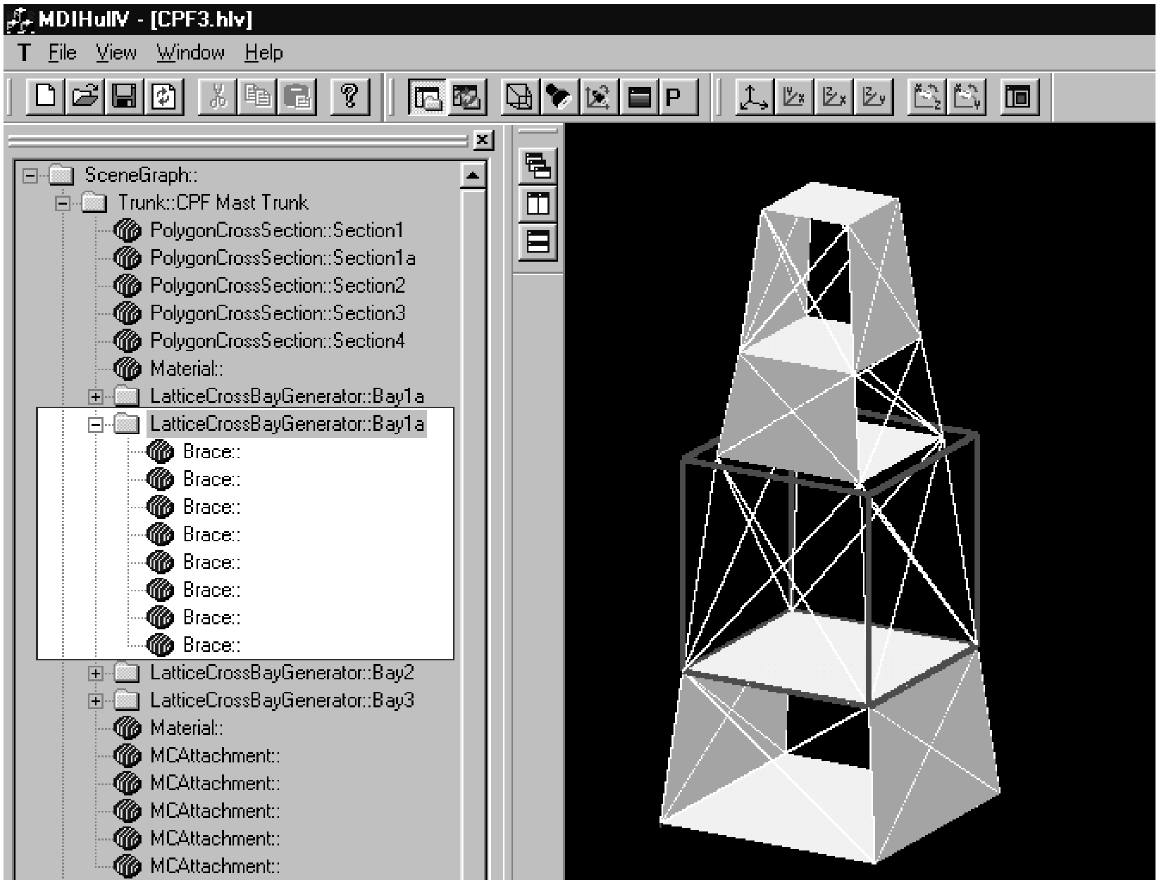


Figure 5.6: Mast Bay Generator

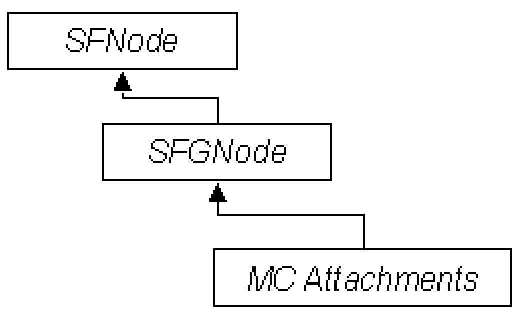


Figure 5.7: MCAttachment Class Hierarchy

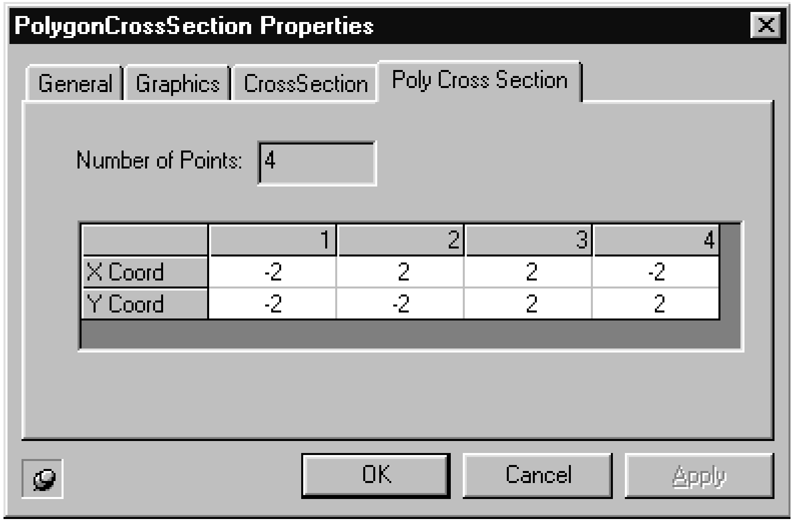


Figure 5.8: Polygon Cross-section Interface

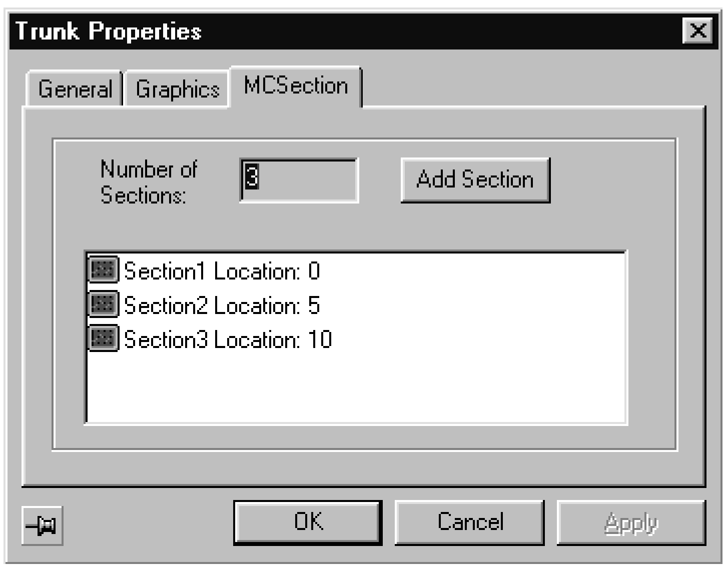


Figure 5.9: MCSS Class Interface

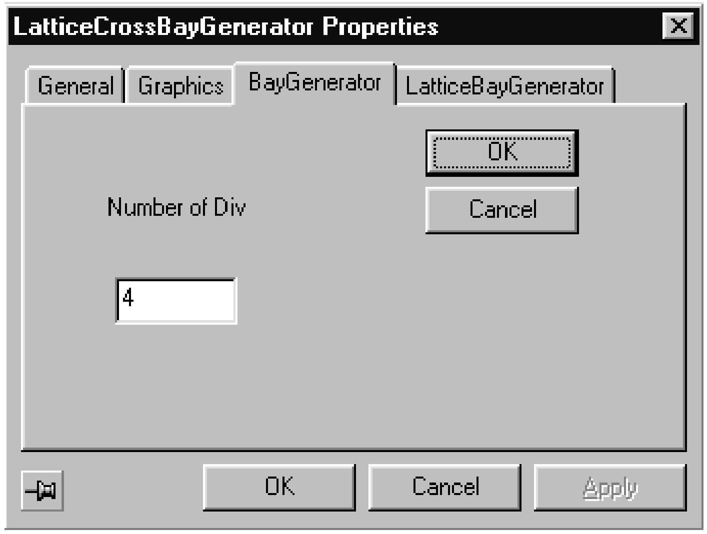


Figure 5.10: Bay Generator Class Interface

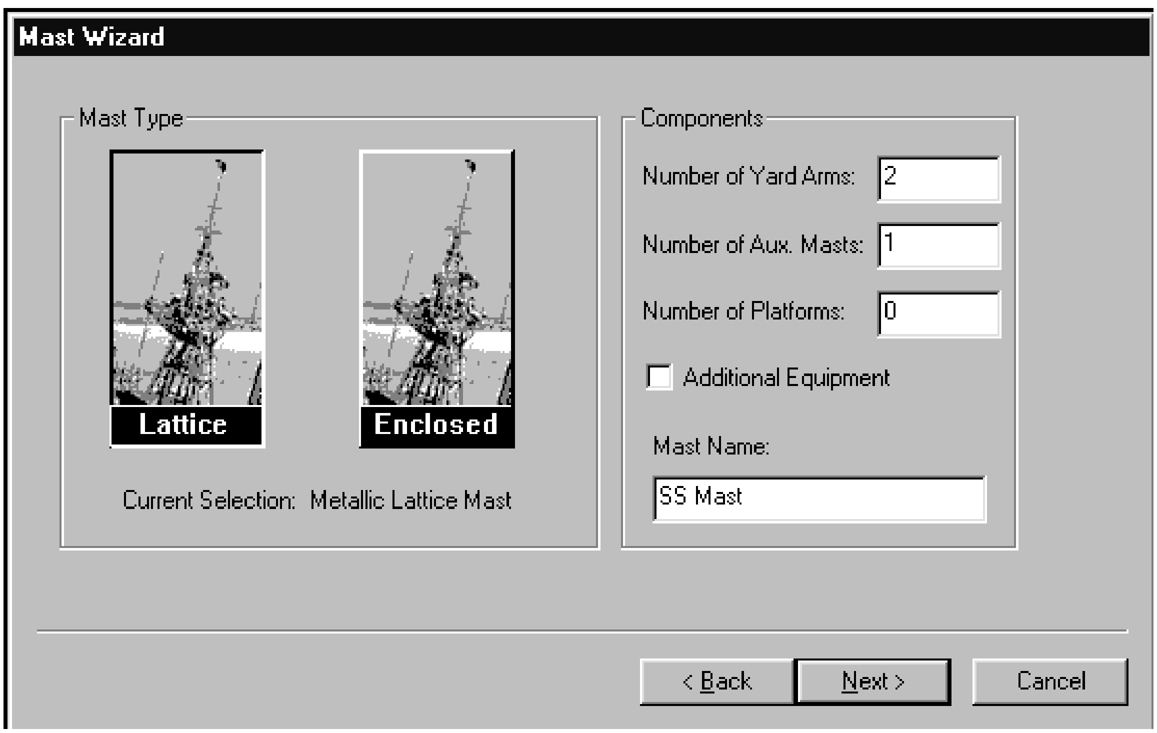


Figure 5.11: First Page of the Mast Wizard

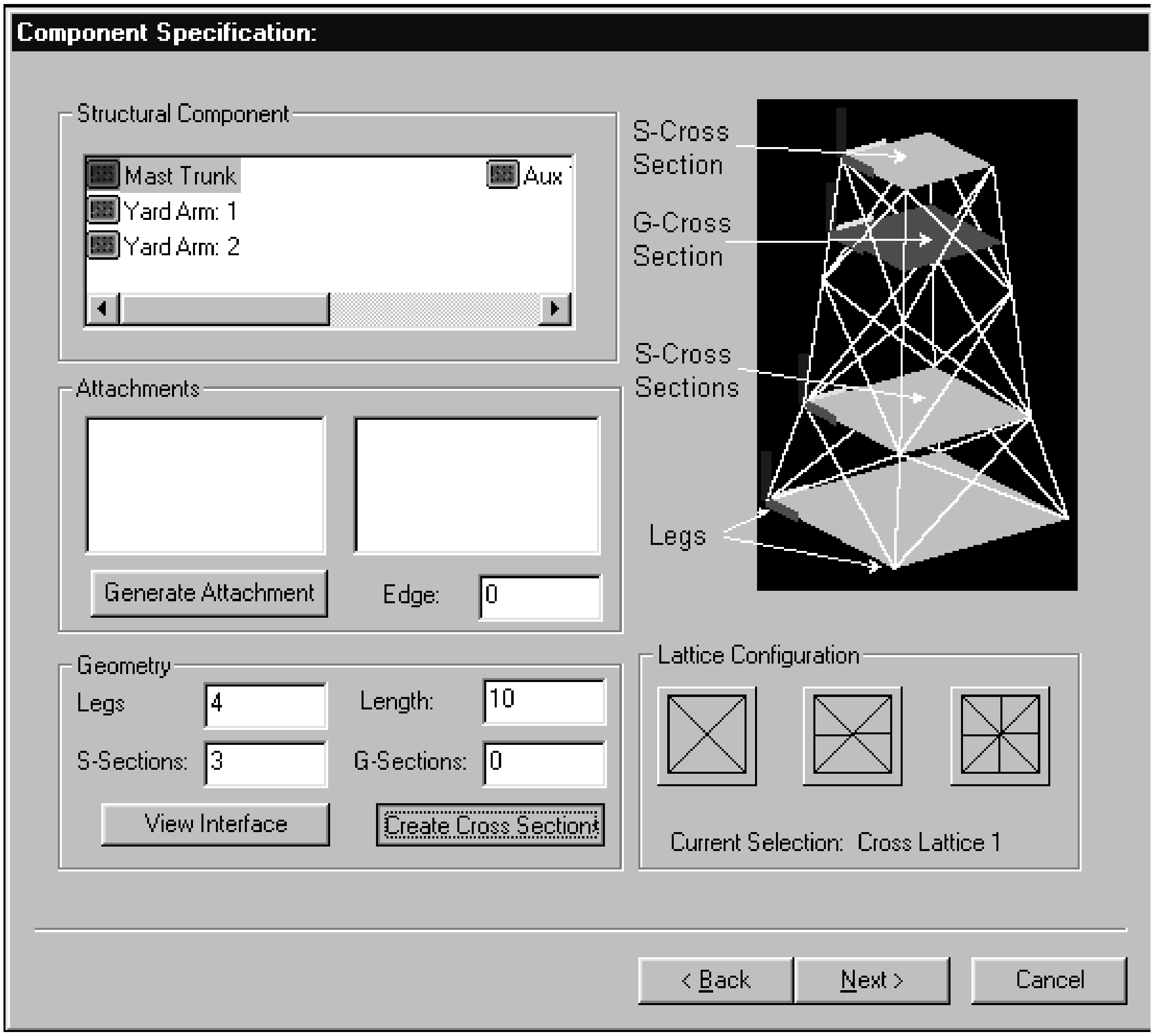


Figure 5.12: Second Page of the Mast Wizard

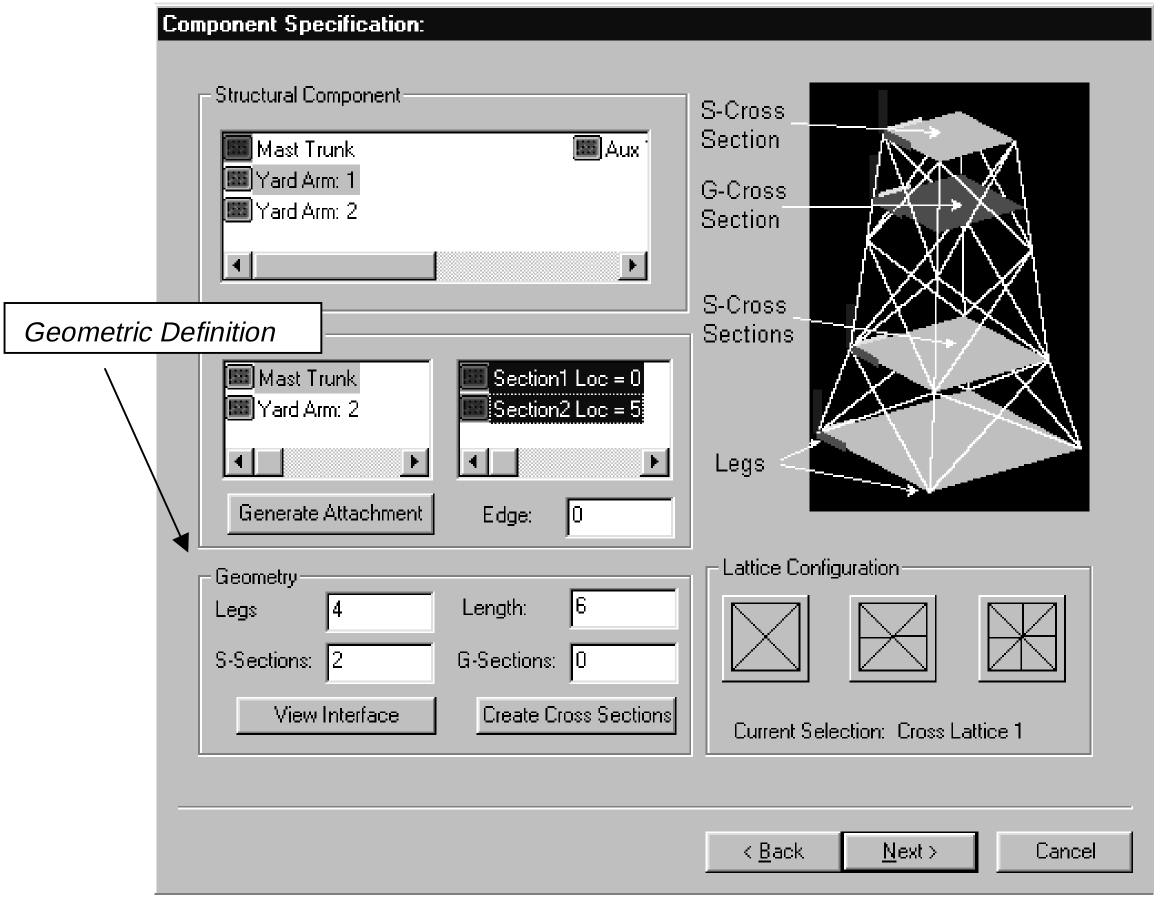


Figure 5.13: Geometry Definition Using the Mast Wizard

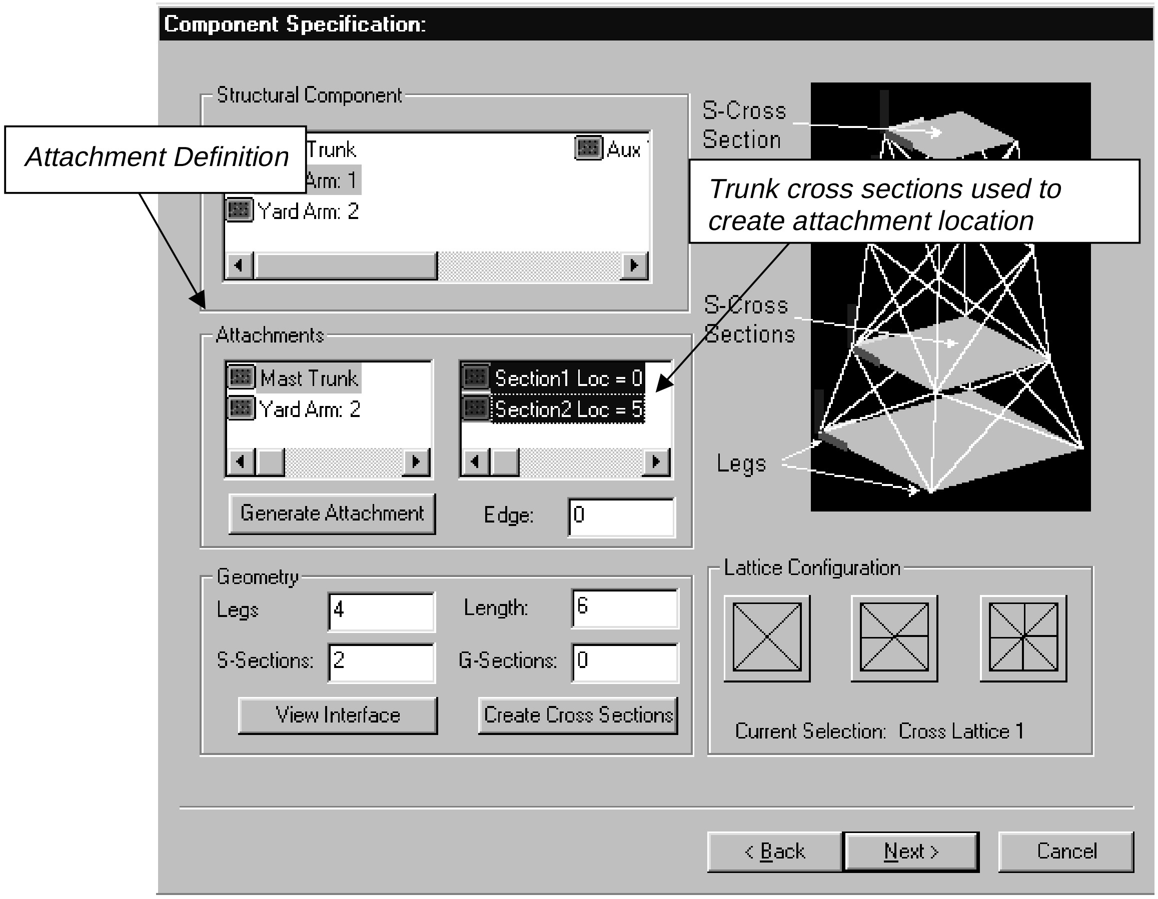


Figure 5.14: Attachment Definition Using the Mast Wizard

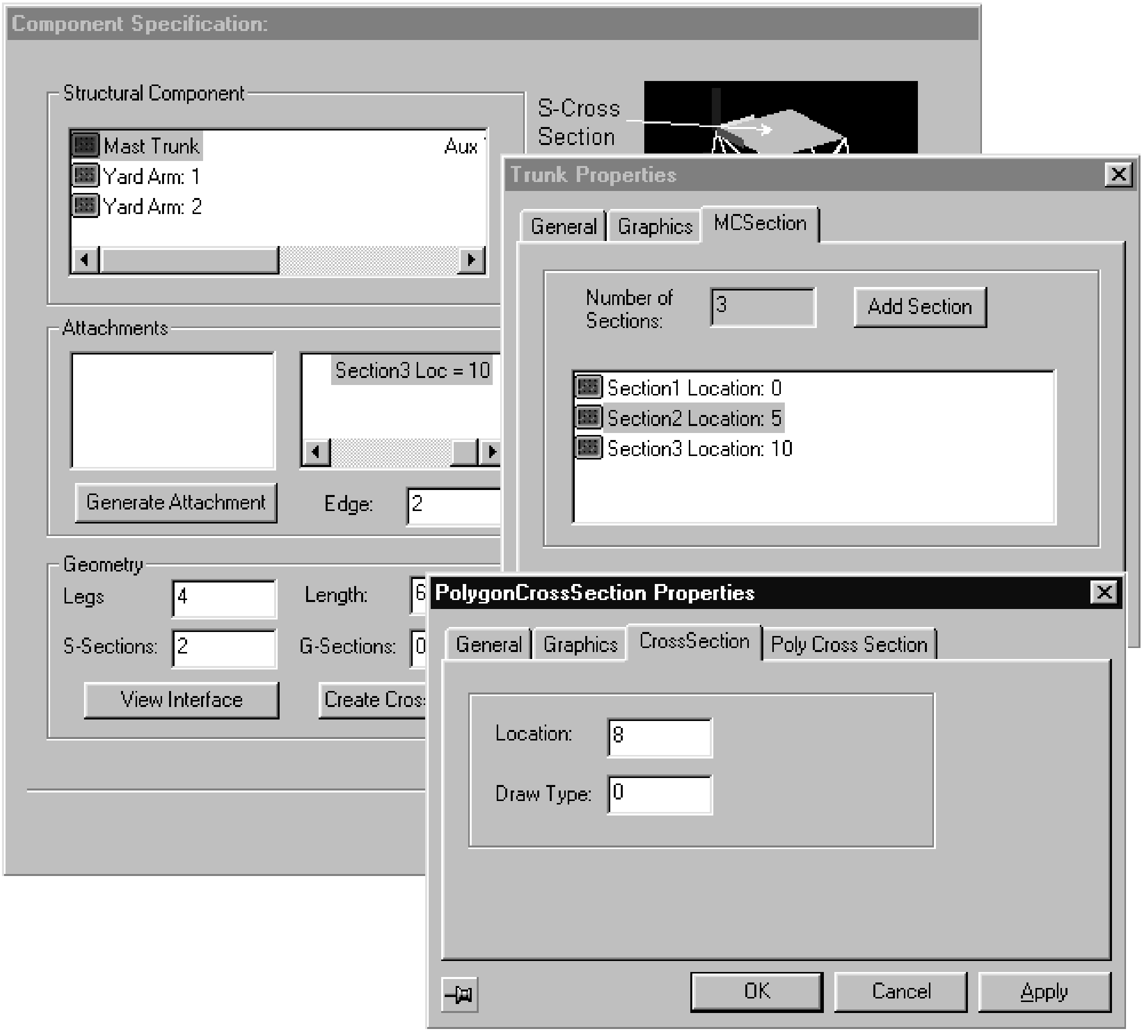


Figure 5.15: Wizard Interface Selection

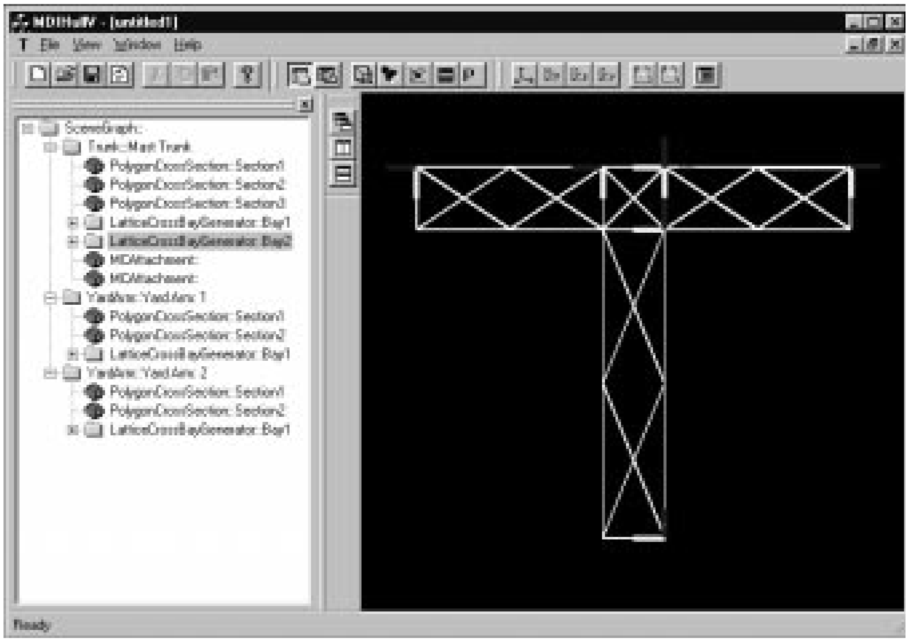


Figure 5.16a: Modifying Cross-section Location (Before)

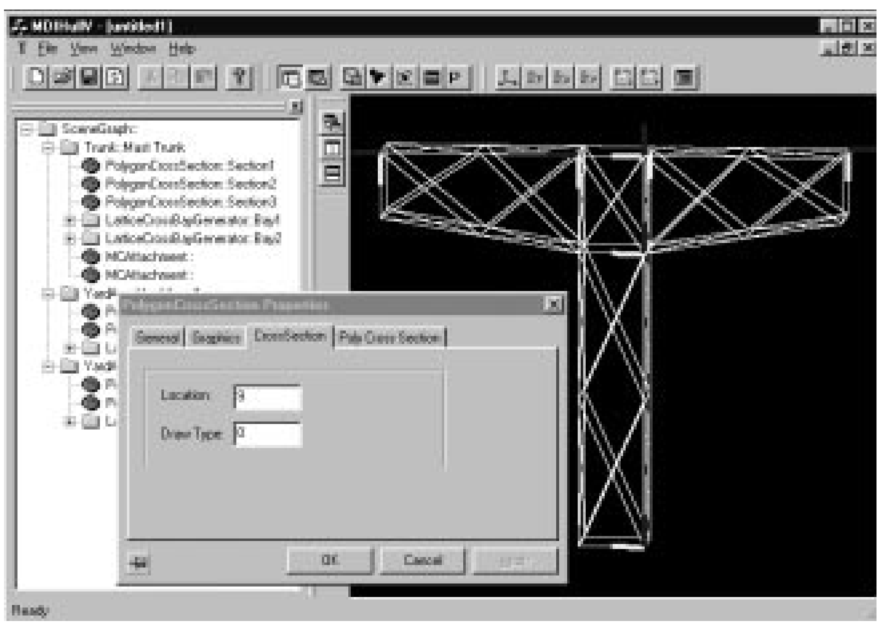


Figure 5. 16b: Modifying Cross-section Location (After)

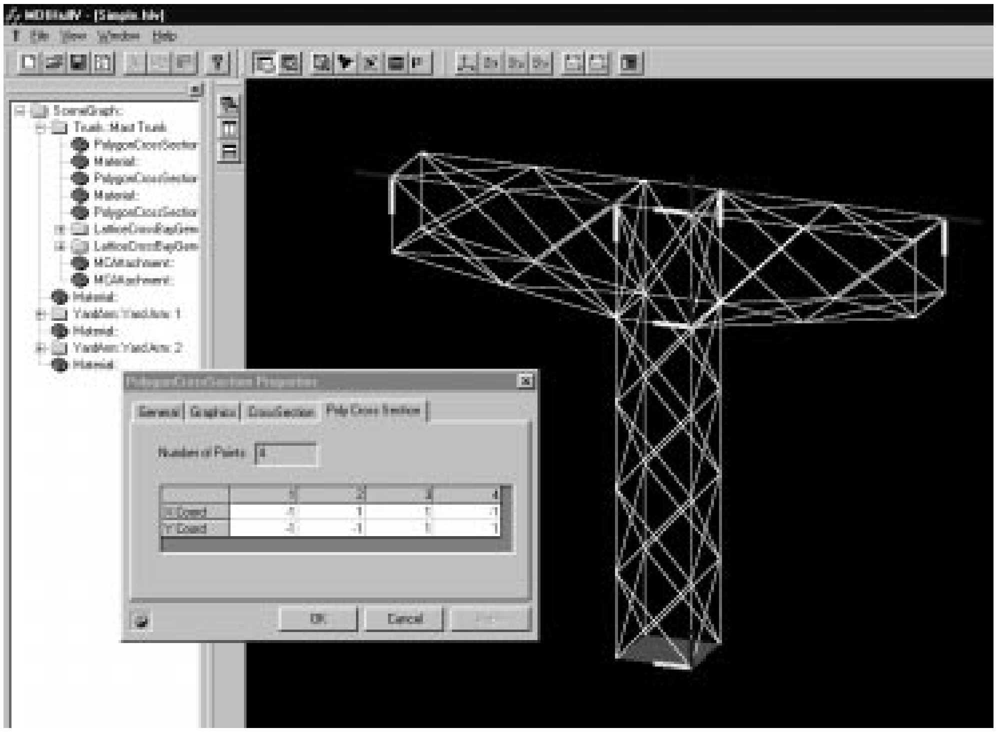


Figure 5.17a: Modifying the Size of the Trunk Base

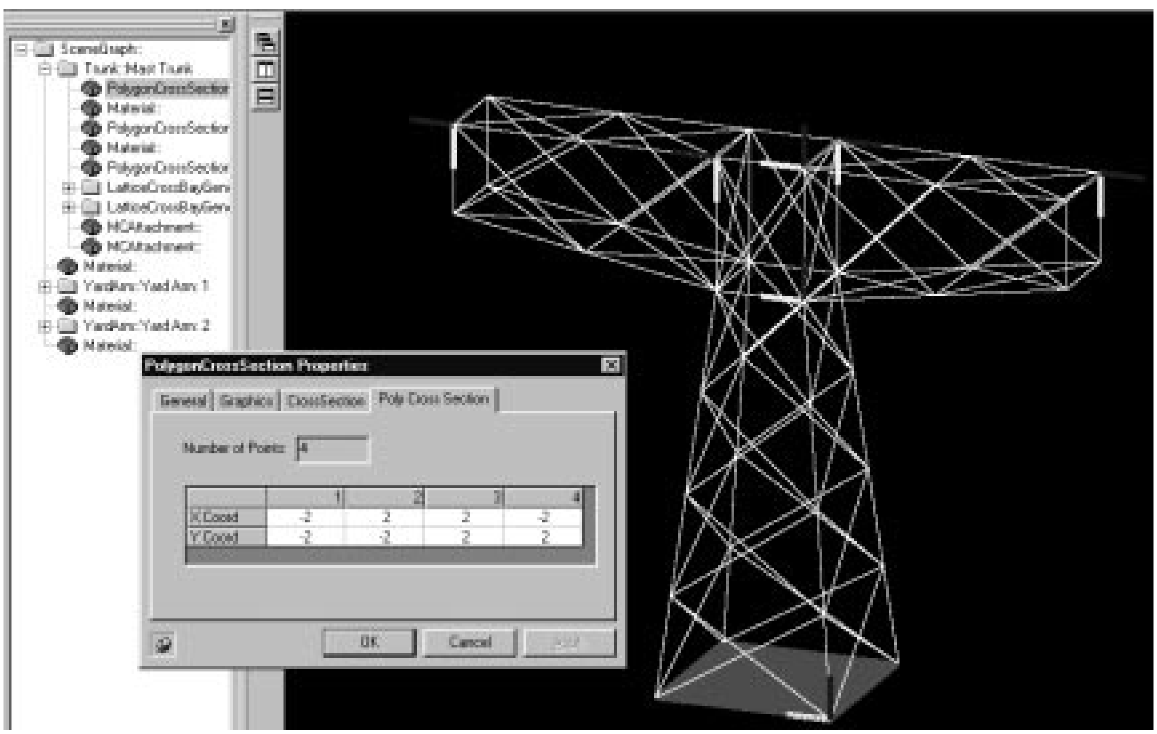


Figure 5.17 b: Modifying the Size of the Trunk Base

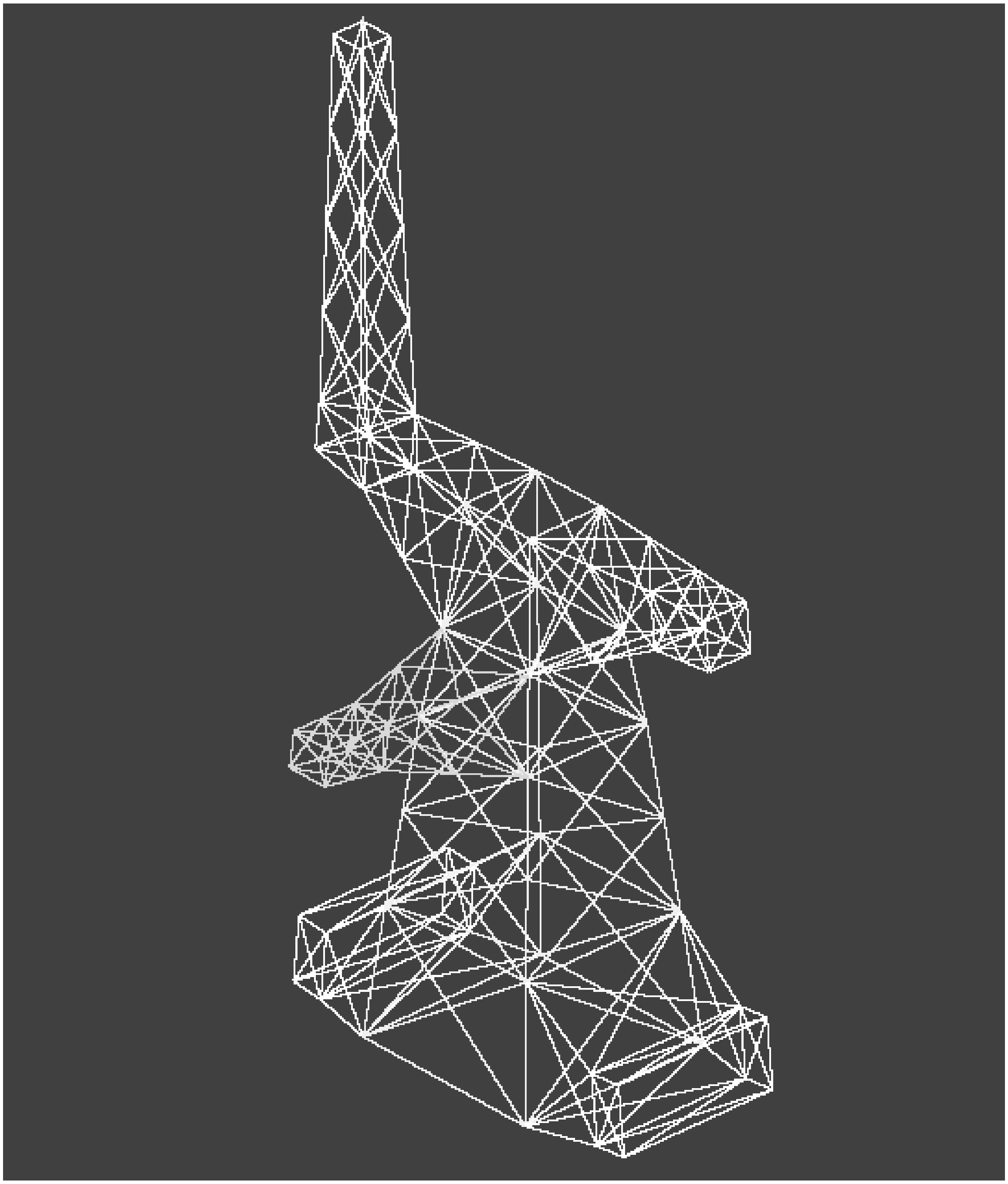


Figure 5.18: Model of Complex Lattice Mast

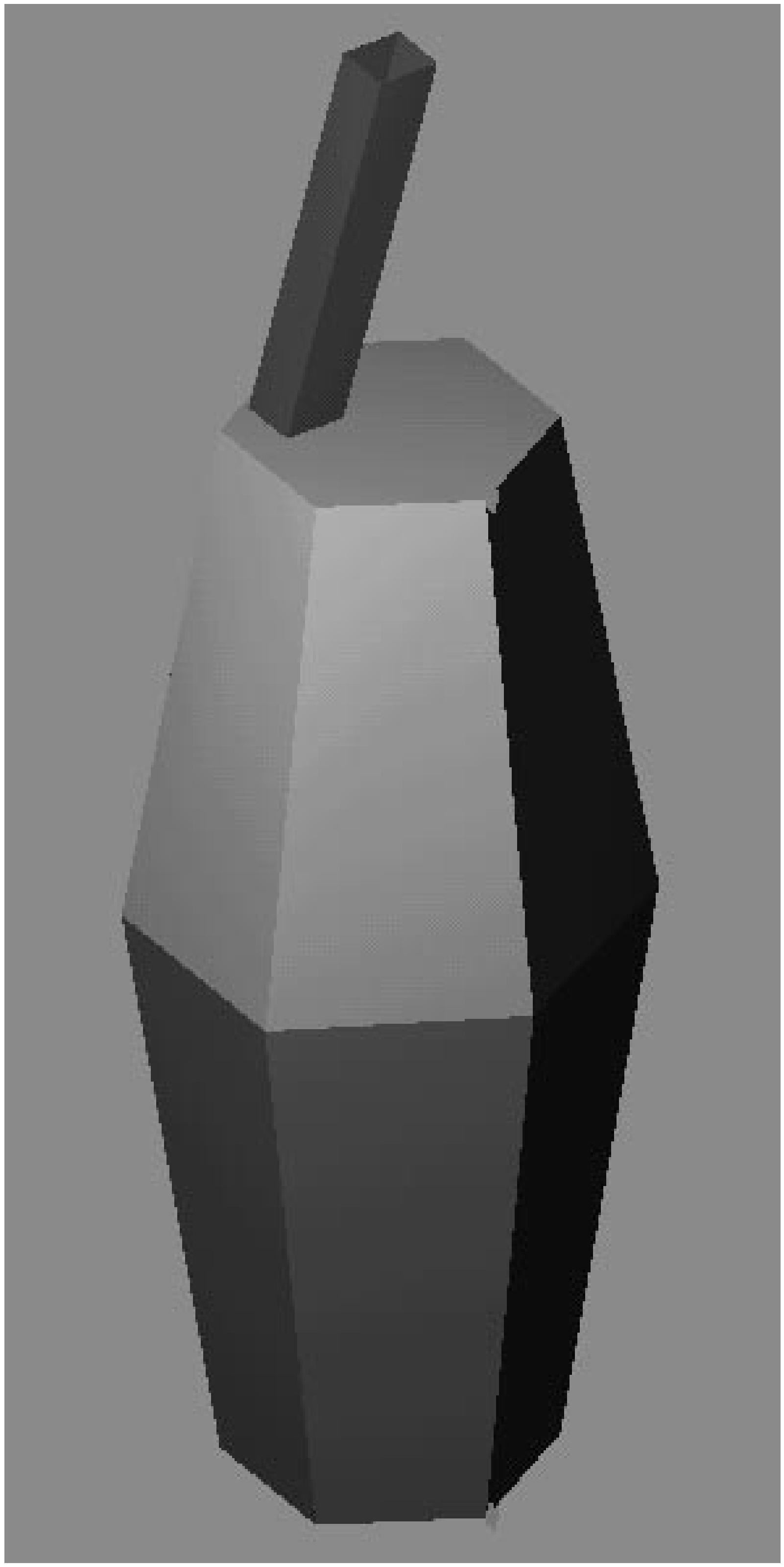


Figure 5.19: Model of Complex Enclosed Mast

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

This study was undertaken to address modelling and analysis capabilities for metallic and composite mast structures, required by DREA in their effort to investigate lightweight masts for the Halifax Class frigate, as part of midlife refit. The study focussed on three main areas. First, an in-depth review of finite element formulations for composite shell structures was performed to provide an understanding of the kinematic theories, failure and damage mechanisms, and element types that can be suitably used for composite mast structures. Next, an overview of metallic and composite mast structures used world-wide was undertaken to identify various mast configurations and finally, the design and development of a prototype mast analysis software (MASTAS) was implemented.

The review of the finite element formulations showed that finite elements focused on three main kinematic theories, namely the equivalent single layer (ESL); layerwise; and 3-D and 2-D continuum theories, and several applications of these theories were reviewed. It was shown that finite elements based on the ESL theories, including the classical laminate plate (CLPT) and first order shear deformation theory FSDT) can provide reasonable approximations of global response quantities such as natural frequencies, buckling loads, strain energy and global displacements. However, when detailed stresses are required at cutouts, connections and other critical locations, the CLPT and FSDT are insufficient and resort must be made to higher order ESL theories or the layerwise theories. Failure of composite structures is based on classical failure criteria, such as maximum stress, maximum strain, Tsai-Hill, and Tsai-Wu. It was shown that the use of the first ply failure concept resulted in conservative designs. For better accuracy, it is necessary to use progressive failure concepts.

In the review of mast structures, various mast types including polemasts (stayed and unstayed), tripod, lattice, and enclosed masts were considered. The polemast is the simplest form of mast construction. Even though it has seen significant use on ships of navies of countries such as the USA, its use in Canada is restricted to auxiliary ships. The lattice mast was by far the most

common type found on Canadian as well as other navy ships. However, this type of mast requires a large amount of space for installation on the ship. The tripod mast, which has the advantage of requiring smaller space for installation is found mainly on ships of the US navy. No applications of this type of mast were found in Canada. The use of enclosed mast structures is an emerging technology that is being considered by several industrialized countries such as the USA, UK and Netherlands, and the feasibility of the concept has been demonstrated in some studies. The most significant of these studies that was found in the open literature is advanced enclosed mast/sensor (AEM/S) that was developed by the USA navy. Most mast structures are constructed of metals such as steel and aluminum. However, the use of metals poses problems such as weight, maintenance (corrosion induced) and electromagnetic interference. Composite materials are now being considered because of their lightweight, high strength and stiffness, good corrosion resistant properties and superior stealth properties. Carbon fiber reinforced plastic (CFRP) composites have long been used for sailboats and glass reinforced plastics (GRP), and hybrid GRP-steel composites are now being applied to tripod and enclosed mast configurations for advanced navy mast structures. These activities are expected to increase in the present decade and beyond.

The review of the various mast configurations provided an insight into the geometrical properties of the components of the mast structures. Based on the results of the review, the requirements of the mast modelling software system were identified and developed. The software system design was also implemented. The design stipulated an object-oriented software for operation in a Windows based operation system on a personal computer (PC). The DREA developed hierarchical object oriented data management (HOOD) toolkit was selected as the software development platform. The HOOD system, incorporating object oriented programming, code reuse, VRML technology, Open GL graphics, and C++ programming, allows for quick software development and maintenance. A prototype software (called MASTAS) based on this design philosophy was developed and demonstrated. It was shown that the program could be used to rapidly generate, plot and manipulate geometric models of mast structures, thus illustrating the feasibility and merit of the software system. Activities required to produce a completely functional software system have been recommended.

6.2 Recommendations for Production Software

As discussed in Chapter 5, a prototype software has been developed in this preliminary study to illustrate the requirements and the object-oriented modelling philosophy set out in Sections 4.2 and 4.3. The prototype software shows the software design and functionality of some of the options, thus confirming the feasibility of the software system. In its present form, the software is capable of rapidly developing lattice and enclosed mast geometries. However, further work is required to bring it up to a fully functional and useable software. This section provides recommendations on the future work required.

Since the requirements and overall scope of the software system are quite extensive, a pragmatic and systematic approach to the development of the software system is required. Such an approach shall involve prioritizing the tasks to be performed so that a useable program can be available in a minimum amount of time, with new features and functionalities being added as time progresses.

Another aspect of the approach shall involve the use of existing tools and modules, as much as is possible. In this regard, the DSA (Norwood, 1999) system, with its warship mast capability, has several tools, modules and features that can be incorporated into the MASTAS system to facilitate the development process, and also reduce the software development costs. In particular, the MGDSA system has legacy codes for computing various types of loads for warship mast structures, as well as tools for assessing the structural integrity of components of latticed masts. It is recommended that these capabilities be exploited in the MASTAS applications.

A two-phase approach is recommended to implement/develop the MASTAS system. These phases may each be performed over a 12 month period. The outcome of the first phase is a functional program complete with all of the basic capabilities that can be used by DREA to develop finite element models of various mast configurations. This will ensure that DREA's work on lightweight masts for the Halifax Class frigates can start in earnest. The outcome of the second phase will be a software system with refined options and advanced capabilities.

Based on the above philosophy, the following tasks/activities are recommended to fully develop and implement the MASTAS system.

Task 1: Preparation/Update of Requirements Document

In this activity, an overview of the prototype software requirements, design and implementation shall be performed. Improvements, modifications and additional capabilities shall be identified with special considerations given to new HOOD capabilities and requirements. Based on these the software requirements document (presented in Sections 4.2 and 4.3) shall be updated and finalized.

Task 2: Modelling Mast Geometry

This task involves the refinement of the geometry modelling capability for lattice and enclosed masts, as well as the development of capabilities for modelling tripod and stayed or unstayed) polemasts.

Task 3: Materials and Property Definitions

In this activity, databases for metal and composite materials shall be developed and means of assigning materials to mast components shall be developed.

Task 4: Finite Element Mesh Generation

This task involves the development of mesh generation capabilities for shells (stiffened or unstiffened), beams and solids. These capabilities shall be provided within the HOOD mesh generation framework. The capability shall be applied to all mast types.

Task 5: Capability of Defining Boundary Conditions

The capability for defining boundary conditions shall be developed in this activity. Provisions shall be made for both automatic and manual generation of boundary conditions.

Task 6: Capability for Load Generation

This task involves the development of capabilities for defining various types of loads (ship motion, wind, blast, live and underwater shock loads) for mast structures. A review of the capabilities in the MGDSA system shall be performed and methods of incorporating these capabilities into the MASTAS system shall be developed and implemented. This is considered the

most cost effective approach for the MASTAS development.

Task 7: Analysis and Design Setup

In this activity modules shall be developed to generate complete finite element model data for selected software systems, such as VAST, ANSYS, and NISA.

Task 8: FE Based Optimization and Structural Integrity Checks

Since the ultimate objective of DREA is to use the MASTAS tool for the analysis/design of various mast configurations, as part of midlife refit, an automatic optimization capability is desirable. This task involves the investigation of the feasibility of developing such a capability in MASTAS. The activities to be performed shall include investigation of the framework for a finite element based optimization scheme for mast structures; investigation of the feasibility of incorporating a specialized solver, based on simple but versatile elements; and the investigation of the structural integrity test methods available in the MGDSA. Based on these investigations, suitable approaches will be recommended and implemented. The capabilities to be developed in this task, will greatly ease DREA's proposed work on lightweight masts, and make the MASTAS system a unique tool.

Task 9: Global-Local Approaches for Connections and Other Details

This task involves the development of global local approaches for modelling and analysis of connections, cutout, thick sections and other critical spots or mast components.

Task 10: Post-Processing Capabilities

This task involves the development of post-processing capabilities. It is our understanding that these capabilities are not of immediate need to DREA. However, development of the capabilities in Task 8 might necessitate availability of post-processing capabilities, depending on the approach taken in Task 8.

Task 11: Interface with FE/CAD Software

This task involves the development of interfaces (both forward and backward) with other finite element and CAD software, as may be required.

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APPENDIX A

A.1 Elastic Coefficients for Orthotropic Material

The elastic coefficients C_{ij} in Eq. 2.8 are related to the engineering constants, E_{ii}, v_{ij} and G_{ij} by (Reddy 1996):

$$
\begin{aligned}
&C_{11} = E_{11}\frac{1-v_{23}v_{32}}{\Delta},\; C_{12} = E_{11}\frac{v_{21}+v_{31}v_{23}}{\Delta} = E_{22}\frac{v_{12}+v_{32}v_{13}}{\Delta} \\
&C_{13} = E_{11}\frac{v_{31}+v_{21}v_{32}}{\Delta} = E_{33}\frac{v_{13}+v_{12}v_{23}}{\Delta},\; C_{22} = E_{22}\frac{1-v_{13}v_{31}}{\Delta} \\
&C_{23} = E_{22}\frac{v_{32}+v_{12}v_{31}}{\Delta} = E_{33}\frac{v_{23}+v_{21}v_{13}}{\Delta},\; C_{33} = E_{33}\frac{1-v_{12}v_{21}}{\Delta} \\
&C_{44} = G_{23},\; C_{55} = G_{13},\; C_{66} = G_{12} \\
&\Delta = 1 - v_{12}v_{21} - v_{23}v_{32} - v_{31}v_{13} - 2v_{21}v_{32}v_{13}
\end{aligned}
$$

where

E_{11}, E_{22}, E_{33} = Young's moduli in 1, 2, and 3 directions, respectively.

v_{ij} = Poisson's ratio in the I-j planes.

G_{23}, G_{13}, G_{12} = shear moduli in the 2-3, 1-3, and 1-2 planes, respectively.

In addition, the following *reciprocal relationship* holds among the principal moduli E_I and Poisson's ratios v_{ij}:

$$\frac{v_{ij}}{E_i} = \frac{v_{ji}}{E_j} (i, j = 1,2,3)$$

APPENDIX A

A.2 Reduced, Transformed Elastic Coefficients for Plane-Stress Orthotropic Material

$$
\begin{aligned}
\overline{Q}_{11} &= m^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + n^4 Q_{22} \\
\overline{Q}_{12} &= m_2 n_2 (Q_{11} + Q_{22} - 4Q_{66}) + (m^4 + n^4) Q_{12} \\
\overline{Q}_{22} &= n^4 Q_{11} + 2m^2 n^2 (Q_{12} + 2Q_{66}) + m^4 Q_{22} \\
\overline{Q}_{16} &= m^3 n (Q_{11} - Q_{12} - 2Q_{66}) + mn^3 (Q_{12} - Q_{22} + 2Q_{66}) \\
\overline{Q}_{26} &= mn^3 (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) + (m^4 + n^4) Q_{66} \\
\overline{Q}_{66} &= m_2 n_2 (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) + (m^4 + n^4) Q_{66} \\
\overline{Q}_{44} &= m^2 Q_{44} + n^2 Q_{55} \\
\overline{Q}_{45} &= mn (Q_{55} - Q_{44}) \\
\overline{Q}_{55} &= n^2 Q_{44} + m^2 Q_{55}
\end{aligned}
$$

where

$\overline{Q}_{11}, \overline{Q}_{12} .... \overline{Q}_{55}$ are the plane-stress reduced and transformed elastic coefficients,
Q_{11},Q_{12},….Q_{66} are the plane stress reduced stiffnesses given by

$$
\begin{aligned}
&Q_{11} = \frac{E_{11}}{1 - v_{12} v_{21}};\ Q_{12} = \frac{v_{12} E_{22}}{1 - v_{12} v_{21}} \\
&Q_{22} = \frac{E_{22}}{1 - v_{12} v_{21}};\ Q_{66} = G_{12} \\
&Q_{44} = G_{23};\ Q_{55} = G_{13}
\end{aligned}
$$

where E_{11}, E_{22} are the Young's modulus in the 1, 2 material principal axes, G_{12}, G_{23}, G_{13} are the shear moduli in the 1-2, 2-3, 1-3 planes, respectively, v_{12} is the major Poisson's ratio in the 1-2 plane, and $v_{21} = v_{12} (E_{22}/E_{11})$.

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This study was undertaken to address modelling and analysis capabilities for metallic and composite mast structures, required by DREA in their effort to investigate lightweight masts for the Halifax Class frigate, as part of midlife refit. The study focussed on three main areas. First, a review of finite element formulations for composite shell structures was performed to provide an understanding of the kinematic theories, failure and damage mechanisms, and element types that can be suitably used for composite mast structures. Next, an overview of metallic and composite mast structures used world-wide was undertaken to identify various mast configurations and finally, the design and development of a prototype mast analysis software (MASTAS) was implemented.

It was shown that finite elements based on the Equivalent Single Layer (ESL) theories, such as the classical laminate plate (CLPT) and first order shear deformation theory (FSDT) can provide reasonable approximations of global response quantities, such as natural frequencies, buckling loads, strain energy and global displacements. On the other hand, higher order ESL theories or layerwise theories would be required to compute detailed stresses at cutouts, connections and other critical locations. It was also shown that for better accuracy of modelling damage in composites, it is necessary to use progressive failure concepts.

There are four main types of masts, namely, polemasts (stayed and unstayed), tripod, lattice, and enclosed masts used on naval ships. The polemast, the simplest form of mast, is found on naval ships, including some auxiliary Canadian vessels. The lattice mast is by far the most common type found on Canadian as well as other navy ships. The tripod mast, which has the advantage of requiring smaller space for installation (compared to the lattice mast) is found mainly on ships of the US Navy but not Canadian ships. The use of enclosed mast structures (metal or composite) is an emerging technology that is being considered by several industrialized countries such as the USA, UK and Netherlands, and some demonstration structures have been reported. Metals (steel and aluminum) are traditionally used for mast construction, but their use poses problems such as weight, maintenance (corrosion induced) and electromagnetic interference. Composite materials are now being considered because of their lightweight, high strength and stiffness, good corrosion resistant properties and superior stealth properties. These activities are expected to increase in the present decade and beyond.

Based on the results of the review, the requirements of the mast modelling software system were identified and developed. The software design specified an object-oriented software for operation in a Windows based operation system on a personal computer (PC). The DREA developed hierarchical object oriented data management (HOOD) toolkit was selected as the software development platform. A prototype software (called MASTAS) was developed. It was shown that the program could be used to rapidly generate, plot and manipulate geometric models of lattice and enclosed mast structures, thus illustrating the feasibility and merit of the software system. Activities required to produce a completely functional software system have been recommended.

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